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FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 77

RBRC Scientific Review Committee Meeting

October 10-12, 2005

Organizer:

N. P. Samios

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~40 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are seventy-six proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. A 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational.

N. P. Samios, Director
October 2005

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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RBRC PUBLICATIONS

Experimental Group Publications **585**

Theory Group Publications **603**

Additional RIKEN BNL Research Center Proceedings Volumes **671**

Contact Information

RBRC Scientific Review Committee Meeting

October 10-12, 2005

Brookhaven National Laboratory, Upton, NY 11973

The eighth evaluation of the RIKEN BNL Research Center (RBRC) took place on October 10-12, 2005, at Brookhaven National Laboratory. The members of the Scientific Review Committee (SRC) were Dr. Jean-Paul Blaizot, Professor Makoto Kobayashi, Dr. Akira Masaike, Professor Charles Young Prescott (Chair), Professor Stephen Sharpe (absent), and Professor Jack Sandweiss. We are grateful to Professor Akira Ukawa who was appointed to the SRC to cover Professor Sharpe's area of expertise. In addition to reviewing this year's program, the committee, augmented by Professor Kozi Nakai, evaluated the RBRC proposal for a five-year extension of the RIKEN BNL Collaboration MOU beyond 2007. Dr. Koji Kaya, Director of the Discovery Research Institute, RIKEN, Japan, presided over the session on the extension proposal. In order to illustrate the breadth and scope of the RBRC program, each member of the Center made a presentation on his/her research efforts. In addition, a special session was held in connection with the RBRC QCDSP and QCDOC supercomputers. Professor Norman H. Christ, a collaborator from Columbia University, gave a presentation on the progress and status of the project, and Professor Frithjof Karsch of BNL presented the first physics results from QCDOC. Although the main purpose of this review is a report to RIKEN Management (Dr. Ryoji Noyori, RIKEN President) on the health, scientific value, management and future prospects of the Center, the RBRC management felt that a compendium of the scientific presentations are of sufficient quality and interest that they warrant a wider distribution. Therefore we have made this compilation and present it to the community for its information and enlightenment.

We thank Brookhaven National Laboratory and the U. S. Department of Energy for providing the facilities to hold this meeting.

N. P. Samios

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973 USA

RBRC Scientific Review Committee (SRC) Meeting
Brookhaven National Laboratory, Upton, NY
Physics Department, Building 510, Open Sessions – Large Seminar Room
October 10, 11 & 12, 2005
Agenda

Committee Members: Jean-Paul Blaizot, Makoto Kobayashi, Akira Masaike, Kozi Nakai, Charles Prescott, Chair; Stephen Sharpe (Absent), Jack Sandweiss, Akira Ukawa
Host: Koji Kaya, Director of Discovery Research Institute, RIKEN, Japan

Monday, October 10, 2005
8:00 AM to 9:00 AM *Open Executive Session & Working Breakfast (Room 2-160)*
(Presentations by RIKEN/RBRC Administration)

Large Seminar Room
9:00 AM to 10:30 AM THEORY GROUP PRESENTATIONS--LARRY MCLERRAN, CHAIR

9:00	Calculations of Cross Sections and Spin Asymmetries In Hadronic Scattering	Werner Vogelsang
9:10	Global Analysis: Update of Fragmentation Functions	Stefan Kretzer
9:20	Single Transverse Spin Physics: From DIS to Hadronic Collisions	Feng Yuan
9:30	Thermalization in the Color Glass Condensate	Kirill Tuchin
9:40	Quarkonia Correlators Above Deconfinement	Ágnes Mócsy
9:50	Properties of the Plasma Created at RHIC	Denes Molnar
10:00	Charge Transfer Fluctuations as a QGP Signal	Sangyong Jeon
10:10	Effective Action for High Energy QCD with the Pomeron Loop	Yoshitaka Hatta
10:20 AM	Break	

11:00 AM to 12:30 PM THEORY GROUP PRESENTATIONS--ANTHONY BALTZ, CHAIR

11:00	Feedback Effects on the Pairing Interaction in Color Superconductors	Kei Iida (Presented by Kenji Fukushima)
	Phase Structure and Instability in Dense Quark Matter	Kenji Fukushima
11:15	Charm Mesons with DWF Quarks on a Quenched 3 GeV Lattice	Shigemi Ohta
11:25	Electromagnetic Properties of Hadrons with Two Flavor Dynamical Domain Wall Fermions	Thomas Blum
11:35	Quarkonia Correlators and Special Functions at T>0	Peter Petreczky
11:45	Spin 3/2 Pentaquark from Lattice QCD Isospin Breaking of Baryon Masses from Lattice QCD	Takumi Doi

Monday, October 10, 2005 (Continued)

Large Seminar Room

11:55	$\Delta I = 3/2$ Kaon Weak Matrix Elements with Non-zero Total Momentum	Takeshi Yamazaki
12:05	Neutron Electric Dipole Moment from Lattice QCD Calculations	Sinya Aoki

12:30 to 1:30 PM *SRC Executive Session - Working Lunch (Room 2-160)*

1:30 PM to 3:00 PM EXPERIMENTAL GROUP PRESENTATIONS --HIDETO EN'YO, CHAIR

1:30	RHIC Heavy Ion Physics	Yasuyuki Akiba
1:45	RHIC Polarimetry	Itaru Nakagawa
2:00	The Pursuit of Polarized Gluon Distribution in the Nucleon with PHENIX	Abhay Deshpande
2:15	Spin Fest--2005 Data Analysis	Yuji Goto
2:30	Relative Luminosity Measurement at PHENIX	David Kawall
2:45	Measurement of Direct Photons in $\sqrt{s} = 200$ GeV p+p Collisions	Kensuke Okada
3:00	Break	

3:30 PM to 4:45 PM EXPERIMENTAL GROUP PRESENTATIONS--GERRY BUNCE, CHAIR

3:30	Spin Dependent Fragmentation Function Results From Belle	Matthias Grosse Perdekamp
3:45	Toward Measuring the Internal Spin-dependent Transverse Momentum of Quarks and Gluons in the Proton at RHIC	Douglas Fields
4:00	CCJ- Status and Progress	Yasushi Watanabe
4:15	A Silicon Vertex Tracker for PHENIX	Atsushi Taketani
4:30	PHENIX Muon Trigger Upgrade	Wei Xie

~5:00 PM *SRC Executive Session (Room 2-160)*

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Tuesday, October 11, 2005

8:00 AM to 8:30 AM *SRC Executive Session and Continental Breakfast (Room 2-160)*

Large Seminar Room

8:30 AM to 10:00 AM QCDSP/QCDOC: Physics Results and Prospects/Project Status

8:30	Overview	Nicholas P. Samios
8:35	RBRC Lattice QCD - An Overview	Norman H. Christ
8:55	Meson Spectrum and Kaon Physics	Christopher Dawson
9:15	Thermodynamics of Strongly Interacting Matter--First Results from QCDOC	Frithjof Karsch
9:35	Beta Decay on the Lattice	Shoichi Sasaki

10:00 AM to 12:30 PM Meetings with Individual RBRC Staff
(Possible Tours)

Theorists (Room 2-160)
Experimentalists (Orange Room)

12:30 PM to 1:30 PM *SRC Executive Session and Working Lunch (Room 2-160)*

1:30 PM to 3:00 PM Meetings with Individual RBRC Staff (Continued)

Theorists (Room 2-160)
Experimentalists (Room 2-78)

3:00 PM to 4:00 PM *SRC Executive Session (Room 2-160)*

4:00 PM to 5:00 PM Meeting with RBRC Administration *(Room 2-160)*

5:00 PM Organizational Meeting for
Review of 5-year RBRC Renewal *(Room 2-160)*

7:00 PM Reception and Dinner (Three Village Inn, Stony Brook) (See Invitation)

Wednesday, October 12, 2005

8:00 AM to 9:00 AM *SRC Executive Session and Continental Breakfast (Room 2-160)*

Room 2-160

9:00 AM to 11:00AM RBRC Proposal for a 5-year Extension of the
RIKEN BNL Collaboration MOU Beyond 2007

9:00 AM	Overview	Nicholas P. Samios
9:20	Spin	Hideto En'yo
9:40	Theory	Larry McLerran
10:00	Break	
10:20	Computing	Norman Christ
10:40	RHIC Operations	Thomas Roser

11:00 AM to 3:30 PM *SRC Executive Sessions and Working Lunch (Room 2-160)*

3:30 PM to 4:00 PM Closeout/Adjourn (Room 2-160)

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RBRC ADMINISTRATION PRESENTATIONS

RBRC Overview

Nicholas P. Samios

RBRC Operations & Accomplishments

Auspicious Year

April 5, 2004	New Discoveries at RHIC Vol. 9 RBRC Scientific Articles
May 14-15, 2004	Workshop: Busza, Gyulassy & McLerran Vol. 62, RBRC Nuclear Phys. A750, March 2005

"One of the major discoveries emerging from RHIC is the creation of a form of hot dense (10 to 30 times denser than a nucleon) matter whose properties are consistent with those of a strongly coupled plasma of subatomic quarks and gluons – the so-called quark-gluon plasma that existed a few microseconds after the birth of the universe."

August 2005	First Three Years of Operation of RHIC Nuclear Physics A757 (2005).

Run 1	FY 00	Au x Au	200 GeV	1 μb^{-1}
Run 2	FY 01-02	Au x Au	200 GeV	10 μb^{-1}
Run 3	FY 03	d x Au	200 GeV	50 nb^{-1}
Run 4	FY 04	Au x Au	200 GeV	1300 μb^{-1}
			62 GeV	20 μb^{-1}
		$\vec{p}$ x $\vec{p}$(30%pol)	200 GeV	3 pb^{-1}
Run 5	FY 05	Cu x Cu	200 GeV	15 nb^{-1}
			62 GeV	0.5 nb^{-1}
		$\vec{p}$ $\vec{p}$ (50% pol)	200 GeV	12 pb^{-1}
Run 6	FY 06	$\vec{p}$ $\vec{p}$ (70% pol)	200 GeV	20-100 pb^{-1}

The Relativistic Heavy Ion Collider Run-5
Copper-Copper Operation 2004/05

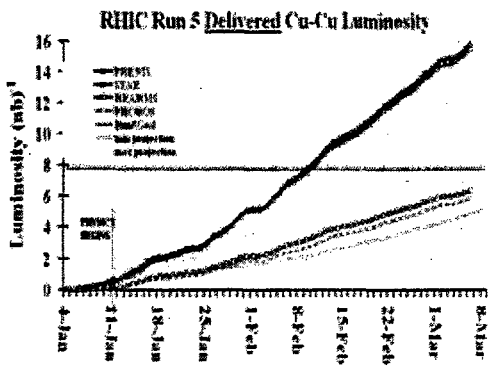
Integrated Cu-Cu Luminosity
[delivered to Phenix, in nb^{-1}]

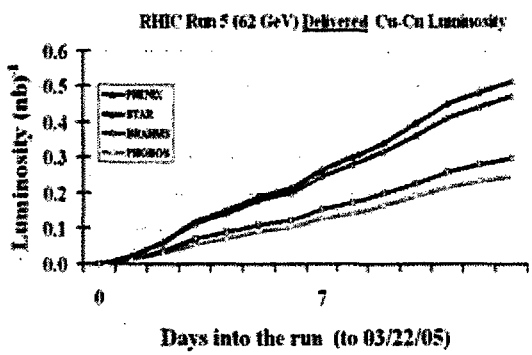
Total [100GeV/u]	Total [31GeV/u]
15.16	0.520
[..]	[...]

[Brahms] [Star] [Phenix] [Phobos] [Beam Experiments] [RHIC Runs Overview]
[RHIC AGS Machine Status] [Scheduling Physicist] [Machine/Detector Planning]

[C-AD Broadcast] [Ring Temperatures]
[Booster/AGS/RHIC Parameters] [Operations] [RHIC Operations] [Controls] [QLI Analysis] [Injection Stats]
[Elogs] [OC Elog] [CuCu Elog] [Shift Leaders Schedule] [Configuration Control] **[Plan of the Day]**

Run-5 preparation:
- Retreat Summary
- Projections
- Injector parameters
- Run-5 parameters
- Injectors List Organization





Total delivered luminosities:
(from January 11, 2005)

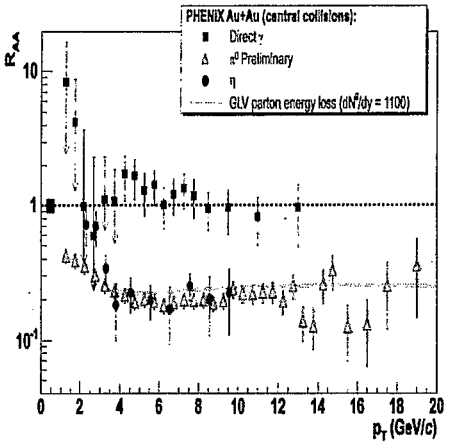
Experiment	100GeV/u [in nb^{-1}]	31.2GeV/u [in μb^{-1}]
Phenix	15.16	520
Star	14.99	470
Brahms	6.15	300
Phobos	5.67	250

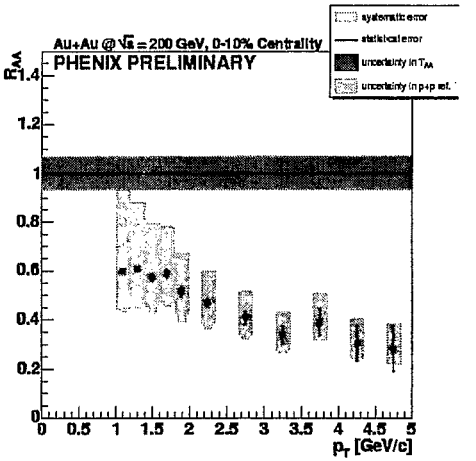
[Run-4] [Dry Run 1] [Dry Run 2] [Dry Run 3] [Start Up Cu Injectors] [Start Up Cu 100GeV/u]
[Run Schedule] [Run-5 History] [Run-5 Weekly Status]

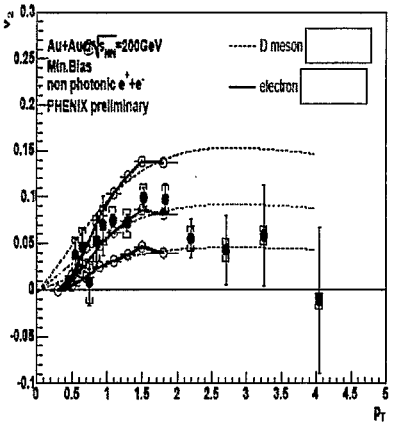
Run Coordinator:	Fulvia Pilat	pilat@bnl.gov	7273 (BNL beeper)	631-576-5475 (cell)	631-344-3134 (office)	631-689-6274 (home)
Deputy:	Mei Bai	mbai@bnl.gov	xxxx (BNL beeper)	631-721-6948 (cell)	631-344-3397 (office)	631-696-1266 (home)

Last modified: Wed Mar 23 010:30 EDT 2005

Put the results together

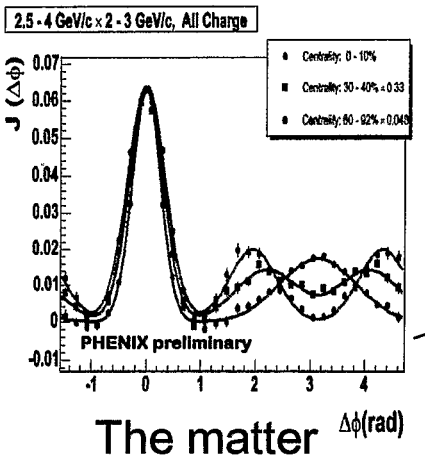






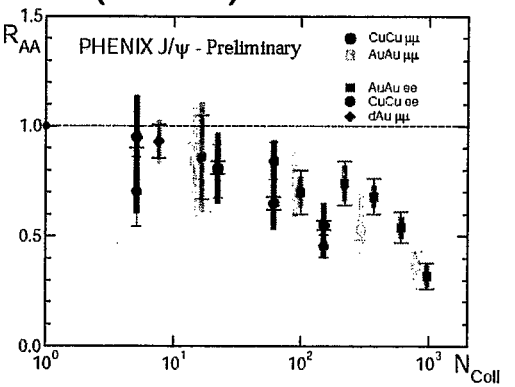
The matter is dense

The matter is strongly coupled

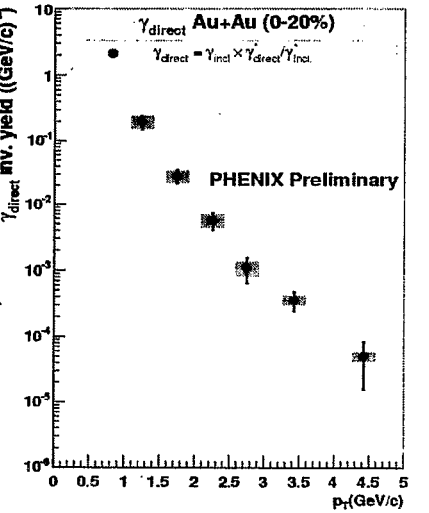


The matter modifies jets

We look forward to working with the theory community to extract the properties of the matter



The matter may melt but regenerate J/ψ's



The matter is hot

Analyzed Runs 1, 2, 3, 4, 5

Run 4	Au x Au	200 GeV/A	1300 μb^{-1}
		62 GeV/A	20 μb^{-1}
Run 5	Cu x Cu	200 GeV/A	15 nb^{-1}
		62 GeV/A	0.5 nb_{-1}

Investigate properties of hot dense matter.

Color Glass Condensate

New Probes: J/ψ

Direct photons

Open Charm

The Relativistic Heavy Ion Collider Run-5

Polarized Proton Operation

Avg_Lum [L:cm-2s-1]	Polarization [P]	Fig. of Merit [L*(P1*P2)**2]
6e30	B: 49.5, Y: 44.5	534.5nb-1

Avg Weekly Luminosity	Total Luminosity
1.34pb-1	12.6pb-1

[Star] [Phenix] [Phobos] [Brahms] [RHICSpin]
[RHIC AGS Machine Status] [Scheduling Physicist] [Beam Experiments]

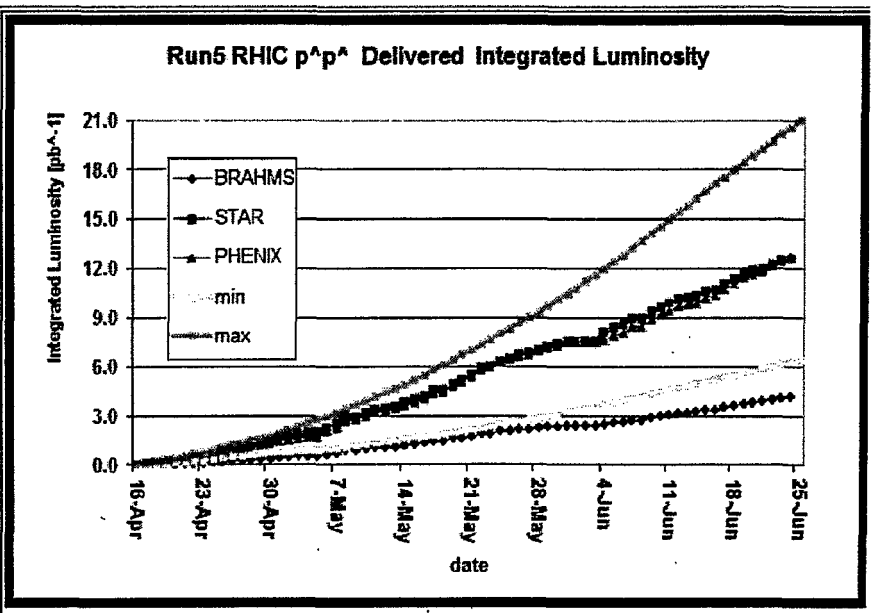
[C-AD Broadcast] [Ring Temperatures] [Retreat 2005]
[Elogs] [OC Elog] [Configuration Control]
[RHIC PP Elog] [RHIC Shift Leaders Schedule] [RHIC Run Plan] [RHIC 205GeV Development Plan]
[AGS PP Elog] [AGS Shift Leaders Schedule] [AGS Run Schedule] [AGS Recipe]

RHIC Parameters:

	energy[Ggamma]	working point(Qx,Qy) for the ramp	lattice(IP 6 8 10 12 2 4)
injection	46.5	B:28.73,29.72, Y:28.72,29.73	10 10 10 10 10 10
ramp	46.5 -- 191.5	B:28.73,29.72, Y:28.72,29.73	beta squeeze
store	191.5	B:28.69, 29.68, Y:28.68,29.69	1 1 10 5 3 10

RHIC
TimeLine

- AGS pp Setup: March 3 --
- RHIC pp setup: March 24 0800 -- March 30 0800
- Access: March 30 0800 -- April 1 0800
  - Jet installation
  - CNI installation
  - AGS cold snake installation
- Ramp development: April 1 0000 -- April 17 0000
- Physics Run:
  - Start: April 17 0000. RHIC fill: 06905
  - End: June 25 1000. RHIC fill: 07327



RHIC performance:

- **Luminosity performance:**
  - **a total of 12.6pb-1 with longitudinal polarization**
  - **a total of 160nb-1 with vertical polarization was recorded by experiments**
- **Polarization performance:**
  - **Average(Blue/Yellow): 49.5/44.5**
  - **maximum(Blue/Yellow): 61.9/58.4**
  - **205 GeV development**
    - **Beam was accelerated to 205GeV. A polarization of 30% was measured in both rings at 205GeV**
    - **Started to provide collisions of 56 bunches at 205 GeV for Physics around midnight of June 3**

Spin Program

All components in place

Polarimeters

Gas jet polarized target

Warm helical snake (RIKEN)

Cold helical snake

Spin rotators and Siberian snakes

Run 4 $\vec{p} \times \vec{p}$ 200 GeV/C 3 pb^{-1}

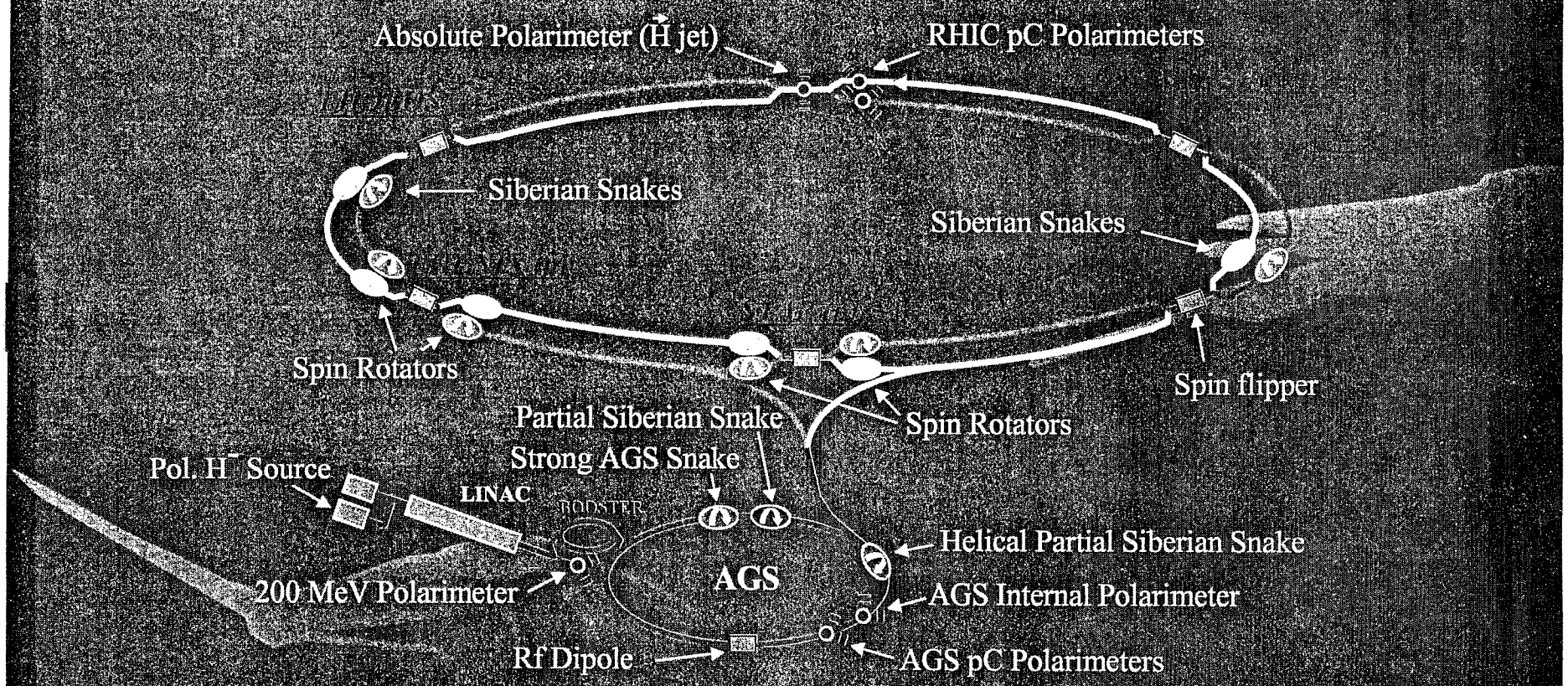
Run 5 200 GeV/c 12 pb^{-1}

Polarization – blue & yellow 45-50%
with cold snake 70% expected

Run 6 200 GeV/c ~50 pb^{-1} FY'06

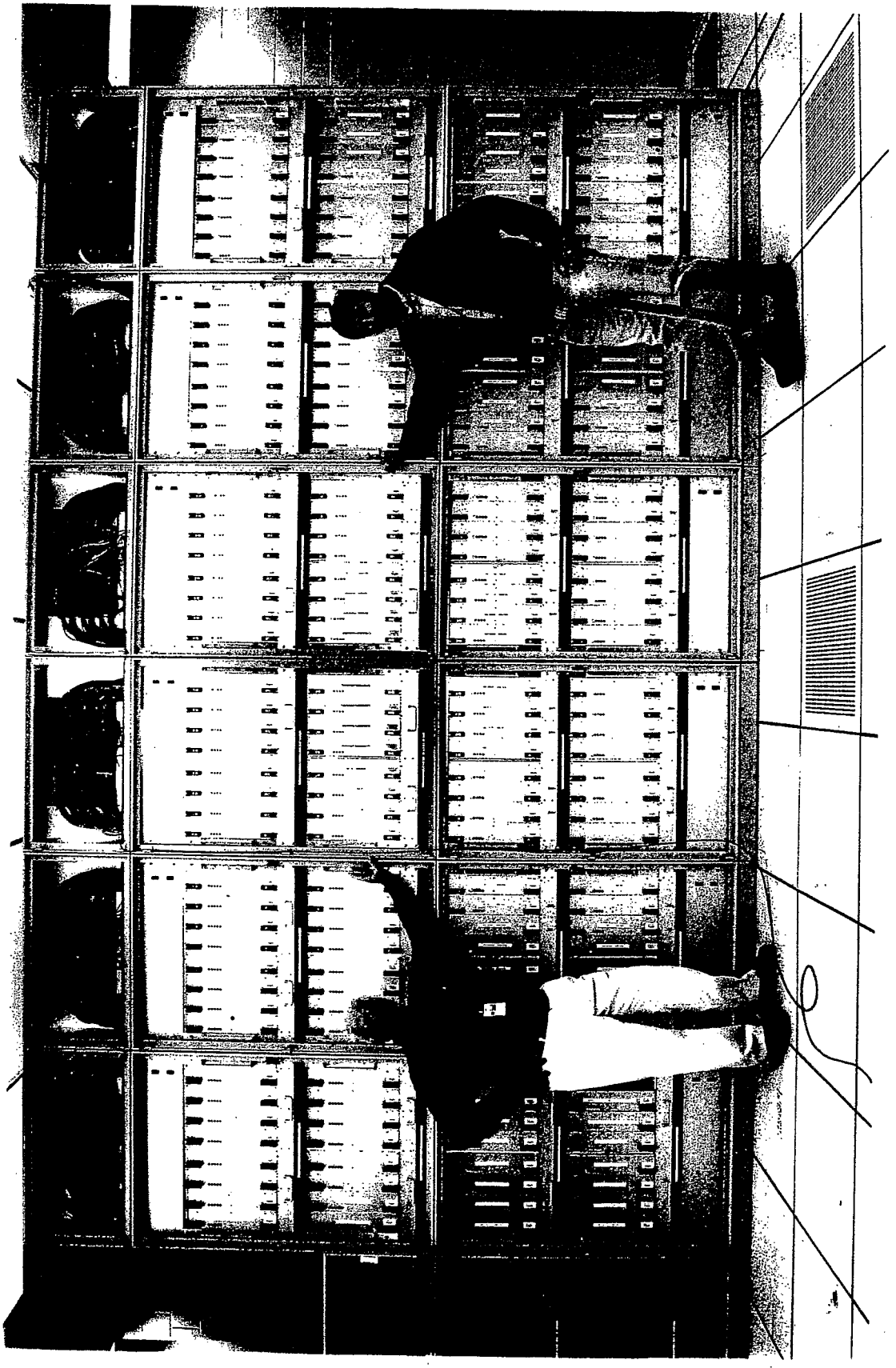
RBRC - Time to exploit the investment in spin program

RHIC pp accelerator complex



QCDSP/QCDOC

QCDSP	Operations (0.6 teraflops)
	Efficiency > 99%
QCDOC	Operational 10 teraflops
	Dedicated May 26, 2005
	90% Lattice QCD
	10% other
UK QCDOC	10 teraflops
	Assembled, tested, shipped
	and operational
DOE QCDOC	10 teraflops
	Assembled, tested and operational



RBRC

Director Emeritus:	T. D. Lee
Director:	N. P. Samios
Associate Director:	H. En'yo
Theory Group Leader:	L. McLerran
Deputy Group Leader:	A. Baltz
Experimental Group Leader:	H. En'yo
Deputy Group Leader:	G. Bunce

Theory Advisory Committee:

T. D. Lee
L. McLerran, Chair
A. Baltz
M. Creutz
F. Karsch
M. Gyulassy
R. Pisarski

Experimental Advisory Committee:

A. Masaike
J. Sandweiss
N. Saito

Workshops/Meetings: 10
Publications: 95 Theory/~60 Experiment
Seminars: 5/week
Other Articles: 1/11

Outstanding Junior Investigator (OJI) Awards

RBRC: Six Awards

Son, D. T.	(2000)
Stephanov, M.	(2001)
van Kolck, U.	(2001)
Schaefer, T.	(2002)
Bass, S.	(2003)
Blum, T.	(2005)

Plenary Speakers at International Lattice Gauge Conference Dublin 2005

Chris Dawson
Taku Izubuchi
Tom Blum
Tilo Wettig (Graduate)

***

Plenary Speakers at QM 2005, Budapest

Dénes Molnár
Kazunori Itakura (Graduate)
Dima Kharzeev (Graduate)
Yasuyuku Akiba

Weekly Seminars

Spin Physics *(Theory & Exp)*	Tuesdays (10:00 a.m.)	Organized by Y. Goto W. Vogelsang A. Deshpande
Nuclear Physics	Tuesdays (11:00 a.m.)	Organized jointly by W. Vogelsang with BNL Staff
High Energy-RIKEN Theory	Wednesdays (1:30 p.m.)	Organized jointly by S. Ohta with BNL Theorists
QCD and RHIC Physics *(Theory & Exp)*	Thursdays (12:30 p.m.)	Organized by P. Petreczky K. Iida
Nuclear Physics-RIKEN Theory	Fridays (2:00 p.m.)	Organized jointly by P. Petreczky with BNL Staff

Future Workshops: RBRC/BNL

Odderon Searches at RHIC
Organizers: Wlodek Guryn, Yuri Kovchegov,
Larry Trueman and Werner Vogelsang
Dates: September 13-15, 2005

Heavy Flavor Production and Hot/Dense Quark Matter
Organizers: Yasuyuki Akiba, H.Huang, R. Rapp,
Kirill Tuchin, and Wei Xie
December 12-14, 2005

RHIC Collisions at Low Energies
Organizer: T. Ludlam, et al.
February 2006

RHIC Physics and the Standard Model: A Workshop and Symposium
Organizers: A. Deshpande, D. Kharzeev,
R. Venugopalan and Werner Vogelsang
June 25-30, 2006

New Universities:

Theory

Iowa State University: Kirill Tuchin
Purdue University: Denes Molnar
SUNY, Stony Brook: Urs Wiedemann

Prospective

UCLA
Texas A&M
Penn State

Experiment

U. of Massachusetts, Amherst: David Kawall

New Hires:

Theory:	Post Doc:	Ágnes Mócsy
Experiment:	Fellow:	Kensuke Okada
	Post Doc:	Patricia Liebing

RBRC Experimental Group Overview

Hideto En'yo

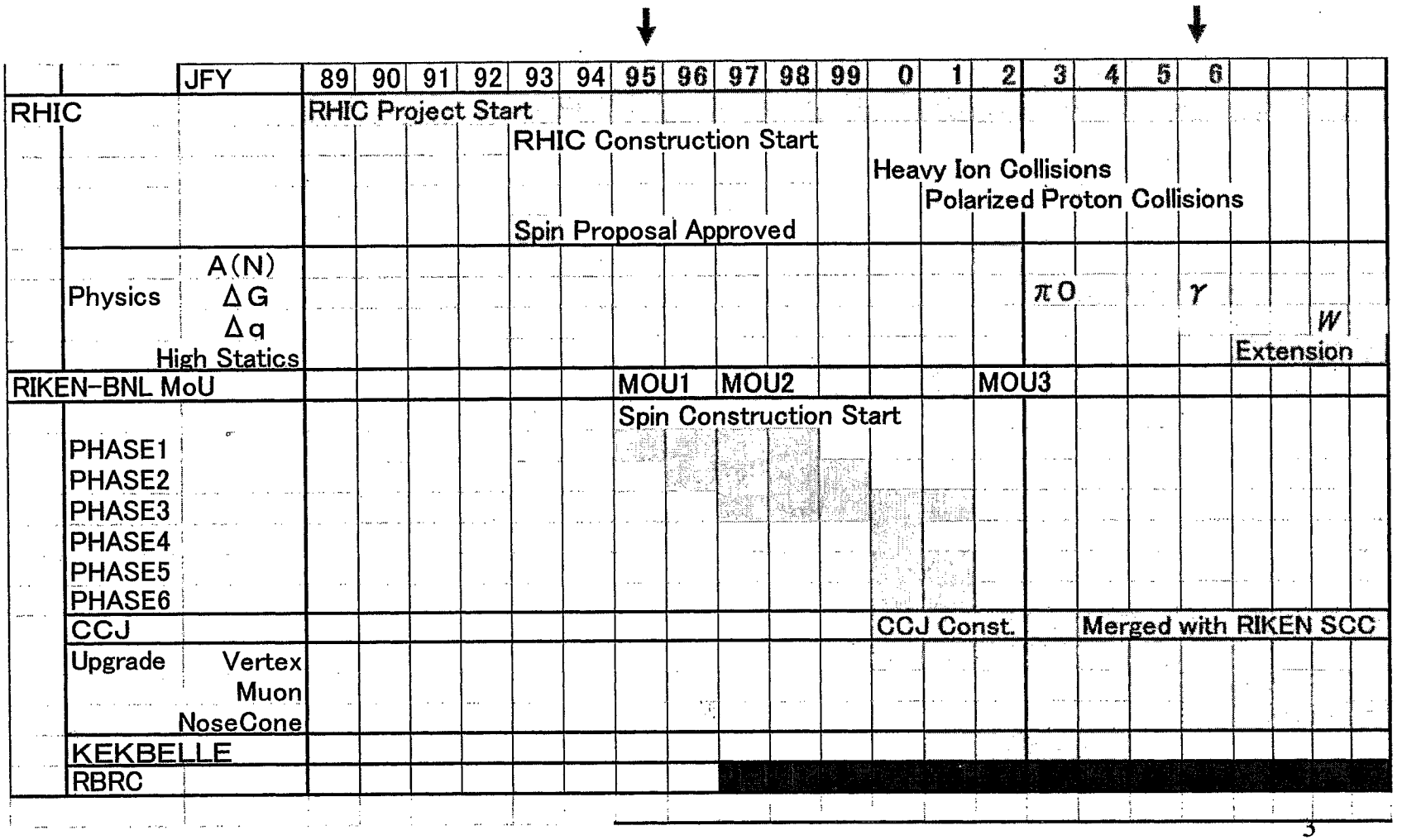
RBRC Experimental Group Overview

RBRC Scientific Review Committee
10-12 October 2005

Hideto En'yo

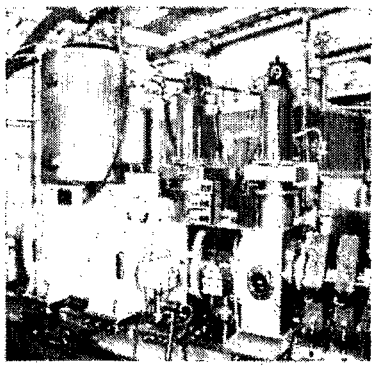
W.Zajc (Colombia U)
Spokes person
E.Obreien (BNL)
OP manager
M.Perdecamp (RBRC)
Deputy Spokes person
Y.Akiba (RIKEN)
Deputy Spokes person
G.Bunce/ deputy
H.Enyo
PHENIX Experiment
15 Nations, 60 Institutes
500 Physicists

History

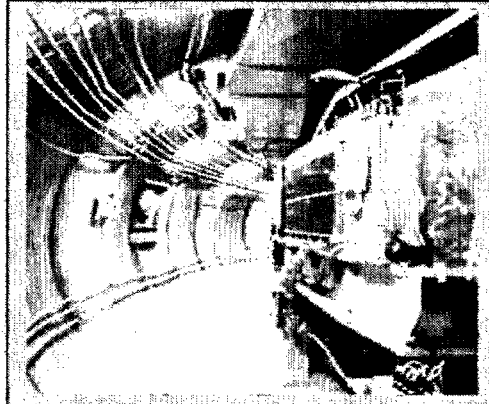

JFY
89 90 91 92 93 94 95 96 97 98 99 0 1 2 3 4 5 6
RHIC
RHIC Project Start
RHIC Construction Start
Heavy Ion Collisions
Polarized Proton Collisions
Spin Proposal Approved
Physics
A(N)
ΔG
Δq
High Statics
π0
γ
W
Extension
RIKEN-BNL MoU
MOU1
MOU2
MOU3
Spin Construction Start
PHASE1
PHASE2
PHASE3
PHASE4
PHASE5
PHASE6
CCJ
CCJ Const.
Merged with RIKEN SCC
Upgrade
Vertex
Muon
NoseCone
KEKBELLE
RBRC

Polarized Proton in RHIC

The first spin collider



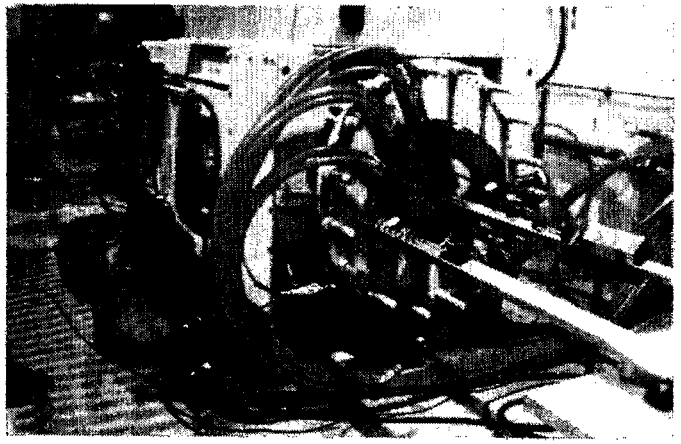
KEK OPPPS, Tuned for RHIC at TRIUMPH

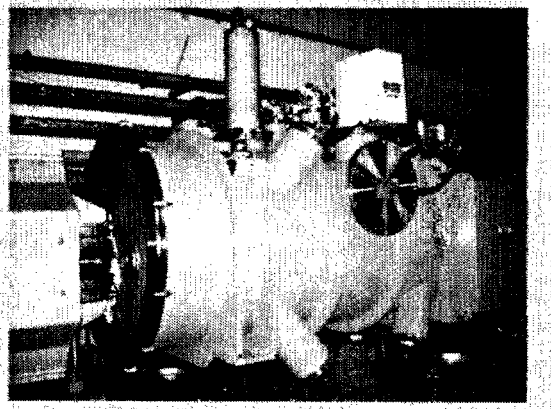


Booster: No Spin Resonance

Snakes and Spin Rotators in the Tunnel

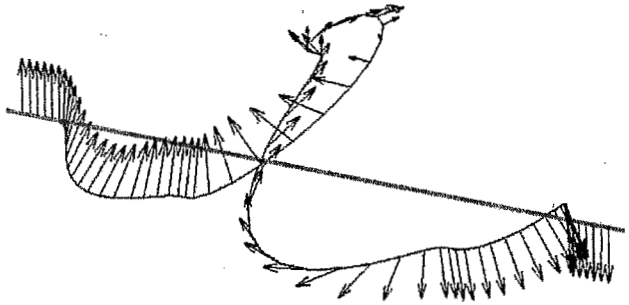
AGS New SNAKE made in RIKEN





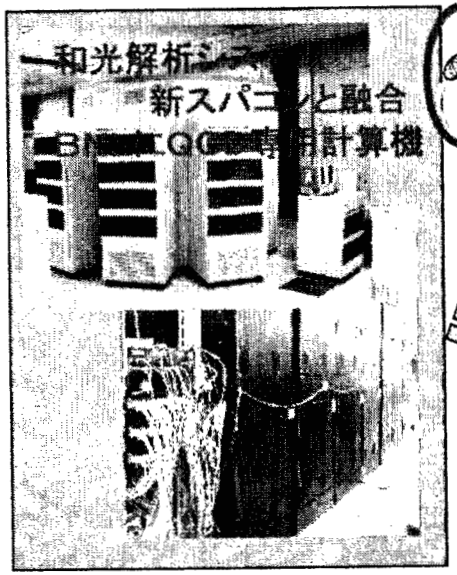
AGS cold snake

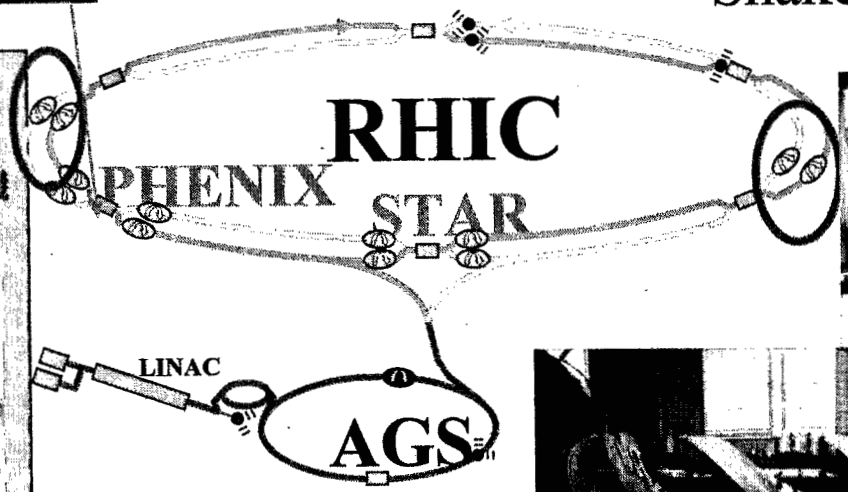
RIKEN construction

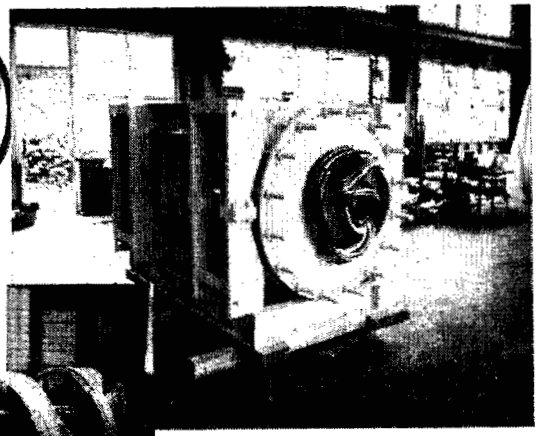


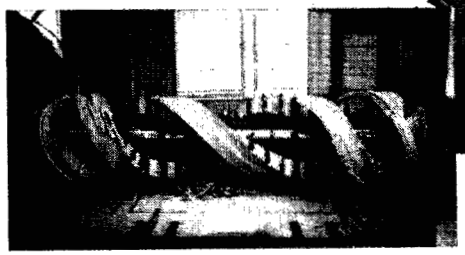
Proton and its spin motion in Snake

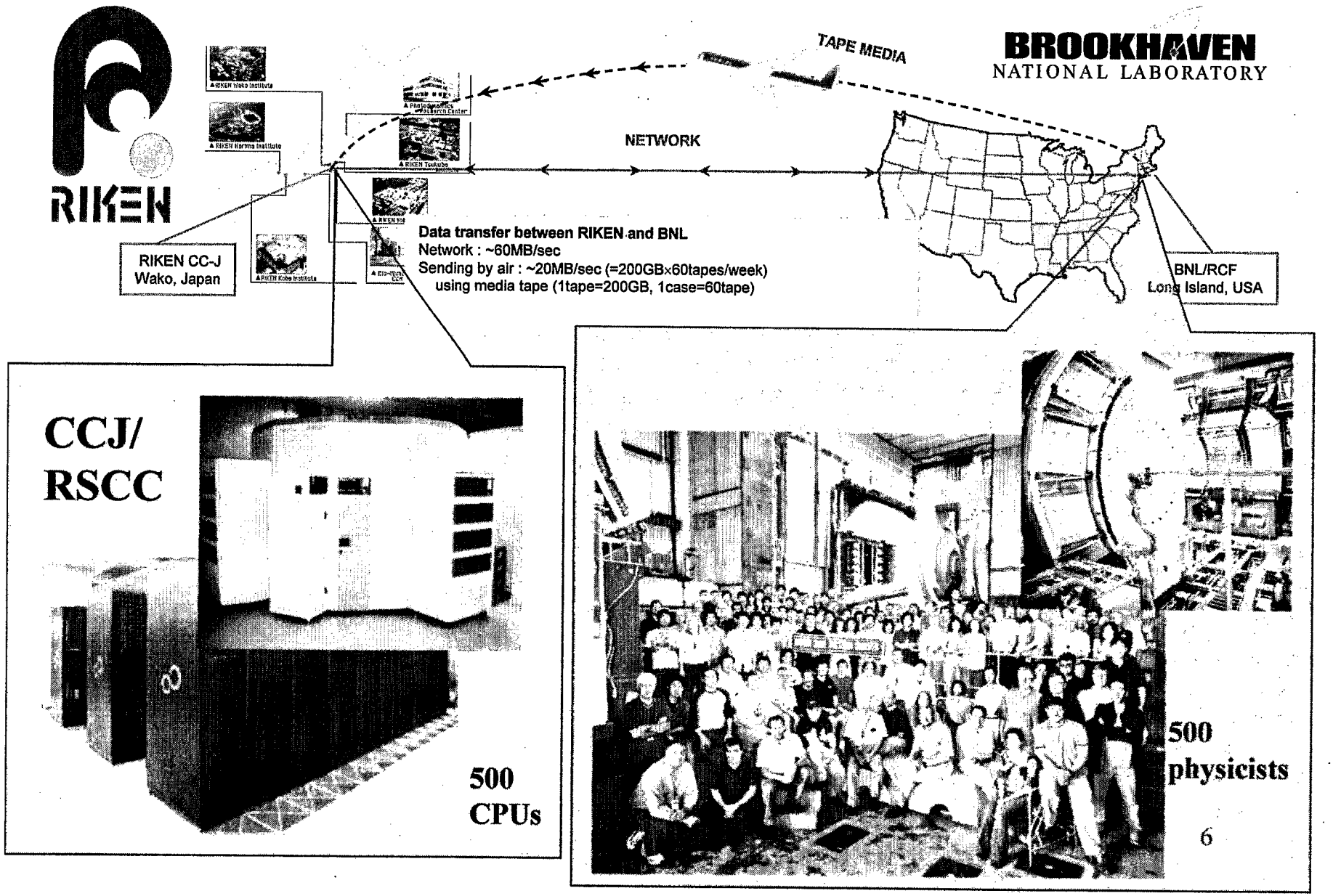
Snake Magnet/Spin Rotator



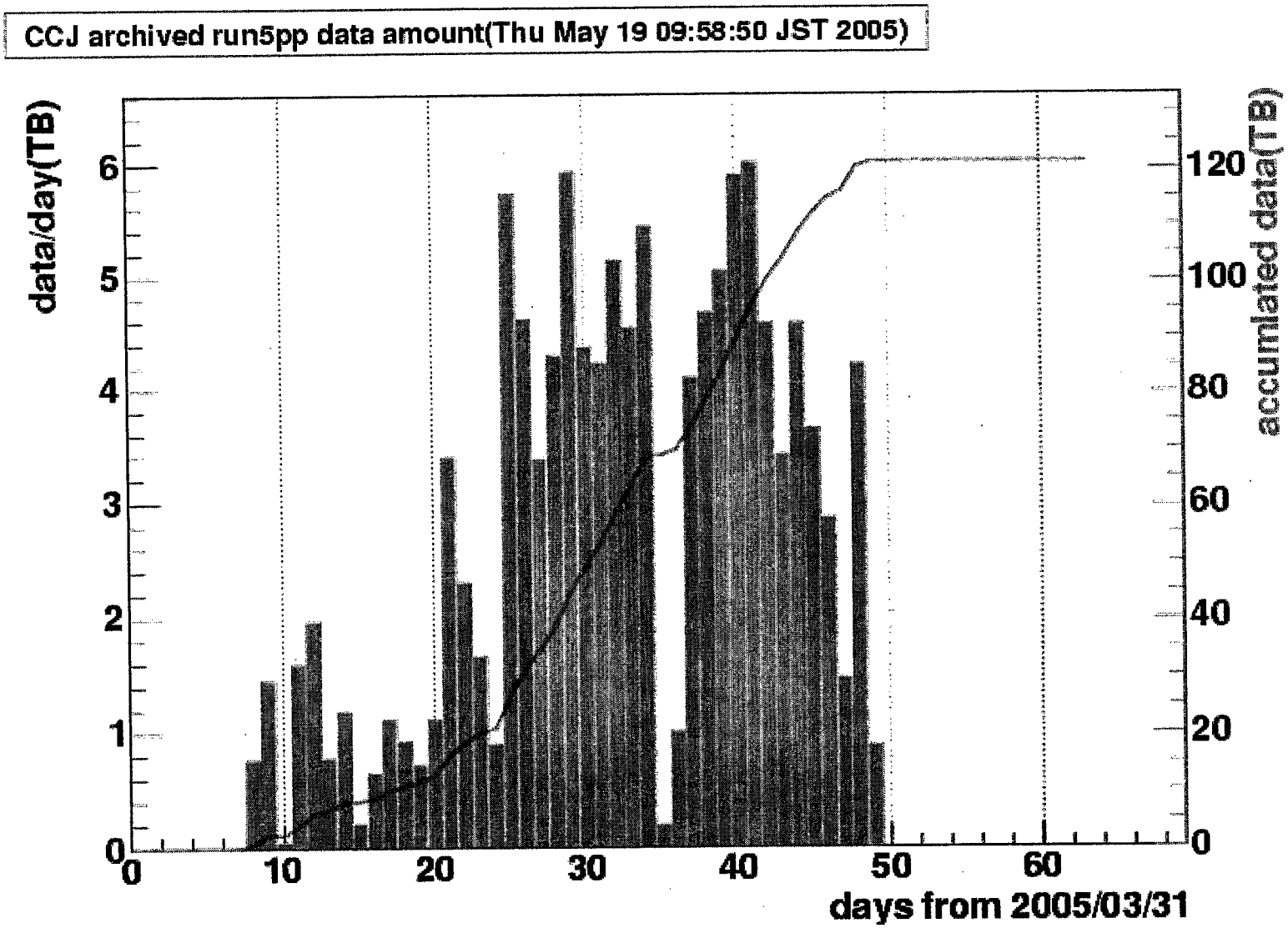







RIKEN
BROOKHAVEN
NATIONAL LABORATORY
TAPE MEDIA
NETWORK
RIKEN CC-J
Wako, Japan
BNL/RCF
Long Island, USA
Data transfer between RIKEN and BNL
Network : ~60MB/sec
Sending by air : ~20MB/sec (=200GB×60tapes/week)
using media tape (1tape=200GB, 1case=60tape)
CCJ/
RSCC
500
CPUs
500
physicists
6

Data transfer challenge over the Pacific with network



Personnel
Status and recent movements

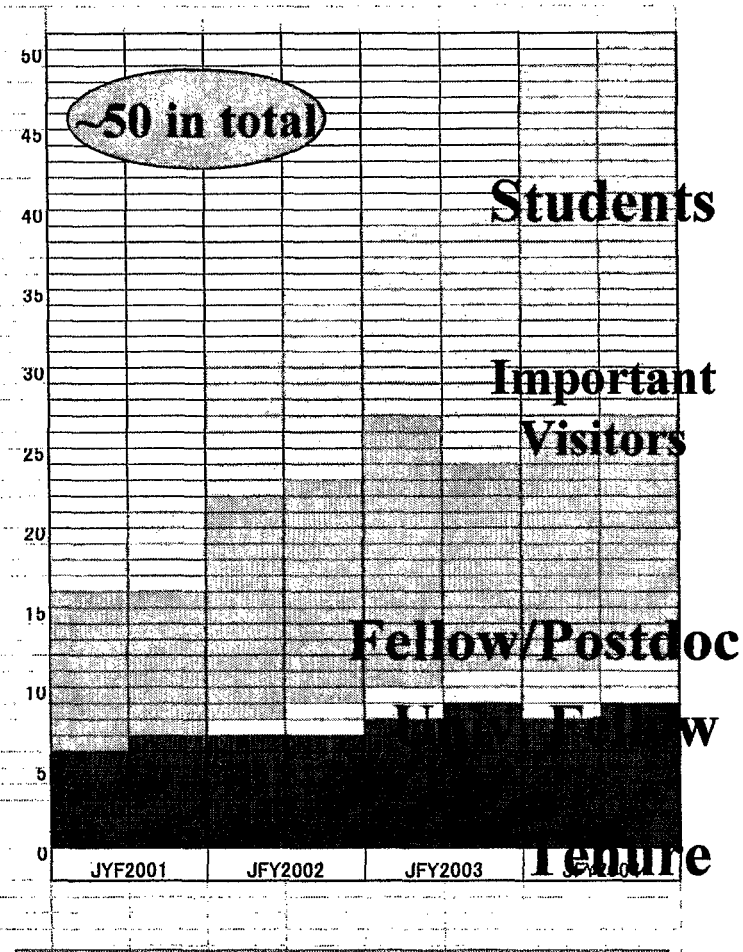
- **RIKEN+RBRC is the second biggest PHENIX participating institute next to BNL.**
- **Yasuyuki Akiba and Matthias Perdecamp are appointed as deputy spokes persons of PHENIX collaboration (two out of two),**
- **Yasuyuki Akiba is responsible for the construction of the vertex detector upgrade in PHENIX.**
- **Since Akiba started, RBRC is expanding QGP physics activity**

Y.Akiba
RHIC Heavy Ion Physics

- **M. Kaneta moved to Tohoku University (tenure)**
- **O. Jinnouchi moved to University of Tokyo (tenure)**
- J. Heuser to GSI and A. Kiyomichi to JAERI (tenure equiv.)
- Dave Kawall (Fellow, starts June 04)
- New RIKEN tenure I. Nakagawa joined 1st of Dec.04
- J. Asai joined 1st of April04, (Kiso Tokken)
- N. Kamihara joined 1st of April05, (Kiso Tokken from JRA)
- S. Kametani and Y. Onuki joined 1st of April05 for Upgrade work at Wako
- **Kensuke Okada will be a new fellow**
- **Patricia Liebing will join in January as New Research Associate**

Member of RBRC Experiment 2004/5

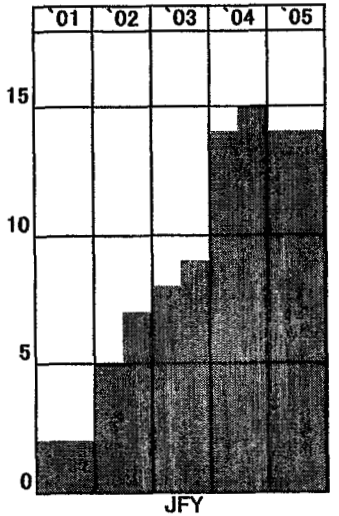
	04 Status		2001		2002		2003		2004	
RBRC	Admin	H.Enyo								
		G.Bunce								
	Fellow	M.Perdecamp				Illinois-U				
		A.Deshpande								
		B.Fox								
		D.E.Fields			NewMexico-U					
		F.Messor								
		A.Bazilevski					BNL			
		W.Xei								
		D. Kawall								
	RA	M.Kaneta								
		K.Okada								
		O.Jinnnouchi								
	RSP RA	H.Kobayashi								
		T.Tabaru								
		T.Kawabata				Tokyo-U				
		H.Torii								
		J. Asai								
	RSP VR	N.Saito			Kyoto U					
		K.Kurita			Rikkyo-U					
		J.Mirata		RIKEN>Rikkyo						
		H.Sato					Kyoto-U			
		S.Lange		Frankfurt-U						
		A.Ogawa		PenState>BNL						
		Z.Li					BNL instrumentation			
		H.Hiejima				Illinois-U				
		M.Wagner								
		R.Seidl								Illinois-U
RIKEN	Tenure	T.Ichihara								
		Y.Watanabe								
		A.Taketani								
		K.Tanida								
		Y.Goto								
		Y.Akiba								
		M.Okamura								
		I. Nakagawa								
	RA	S.Yokkaichi								
		H.Ohnishi								
		J.Tojo								
		T.Chujo								
		R.Rykov								
		J.Hauser								
		K.Hasuko								
		H.Kano								
		A.Kiyomichi								
Student	TITech	N.Kamihara								
		T.Horaguchi								
		K.Nakano								
		H.Kanou								
		J.Takano								
	Kyoto	M.Togawa								
		Y.Fukao								
		H.Okada								
		K.Aoki								
		S.Kohei								
	Heiderberg	V.Siegle								
	Hiroshima	T.Hachiya								
		Y.Tsuchimoto								
	CNS Tokyo	F.Kajihara								
	Rikkyo	Y.Inoue								
	Niigata	K.Fujiwara								
		Total	19	21	31	35	40	40	49	51
		Visitor	0	2	4	5	7	9	8	9
		Students	3	3	5	7	6	7	15	15
		Researcher	16	16	22	23	27	24	26	27



15 Students,
8 Spin, 3 HI, 4 Upgrade

Student Status (RBRC&Wako)

EXPERIMENT		2001	2002	2003	2004	2005	
TITech	N. Kamihara	JRA	JRA	JRA	PT	RSPD	Muon
	T. Horaguchi			JRA	JRA	JRA	Direct Gannma
	K. Nakano				PT	JRA	Jet
	J. Takano				JRA	JRA	Snake Pol-Acceleration
Kyoto	H. Sato	JSPS	JSPS	JSPS			Muon
	M. Togawa		JRA2	JRA2	JRA2	JSPS	Local Polarimeter
	Y. Fukao			JRA	JRA	JRA	Pi-0 Analysys
	H. Okada			JRA2	JRA2	JRA2	Polarimeter
	K. Aoki				PT	JRA2	Muon upgrade
	K. Shoji					PT	Muon upgrade
Niigata U	K. Fujiwara				JRA	JRA	Silicon upgrade
Hiroshima	Y. Tsuchimoto				JRA	JRA	A+A -> electron
	T. Hachiya			JRA2	JRA2		d+A -> electron
U.Tokyo	F. Kajihara				JRA	JRA	A+A -> electron
Rikkyo U	Y. Inoue				PT	PT	
Heiderberg	V. Siegle						Belle
T.U. Muenchen	D. Gabbert						Belle
	R. Seidl						Belle
U.Tokyo	Y. Hatta		JRA	JRA	RSPD	RSPD	High Density
Hiroshima U.	H. Yokoya			JRA	JRA		pQCD
Kanazawa U.	K. Hashimoto				JRA	JRA	Lattice QCD



RBRC Young Researcher
RIKEN Junior Research Associate
RIKEN Student Part Timer
JSPS DC Student
RIKEN Special Doctral Fellowsh PostDOC

This physics program attracts young people.
They graduate, and new ones join.

Experiment G. Organization

UPGRADE@CERN
Hiroaki Ohnishi

BELLE
R. Seidl (RBRC Visitor)
A. Ogawa (RBRC Visitor)

RBRC
Hideto Enyo
Gerry Bunce
Matthias Grosse Perdekamp
Abhay L Deshpande
Douglas E. Field
David Kawall
Xie Wei
Kensuke Okada
(Osamu Jin-nouchi)
(Masashi Kaneta)
Naohito Saito (Visitor)

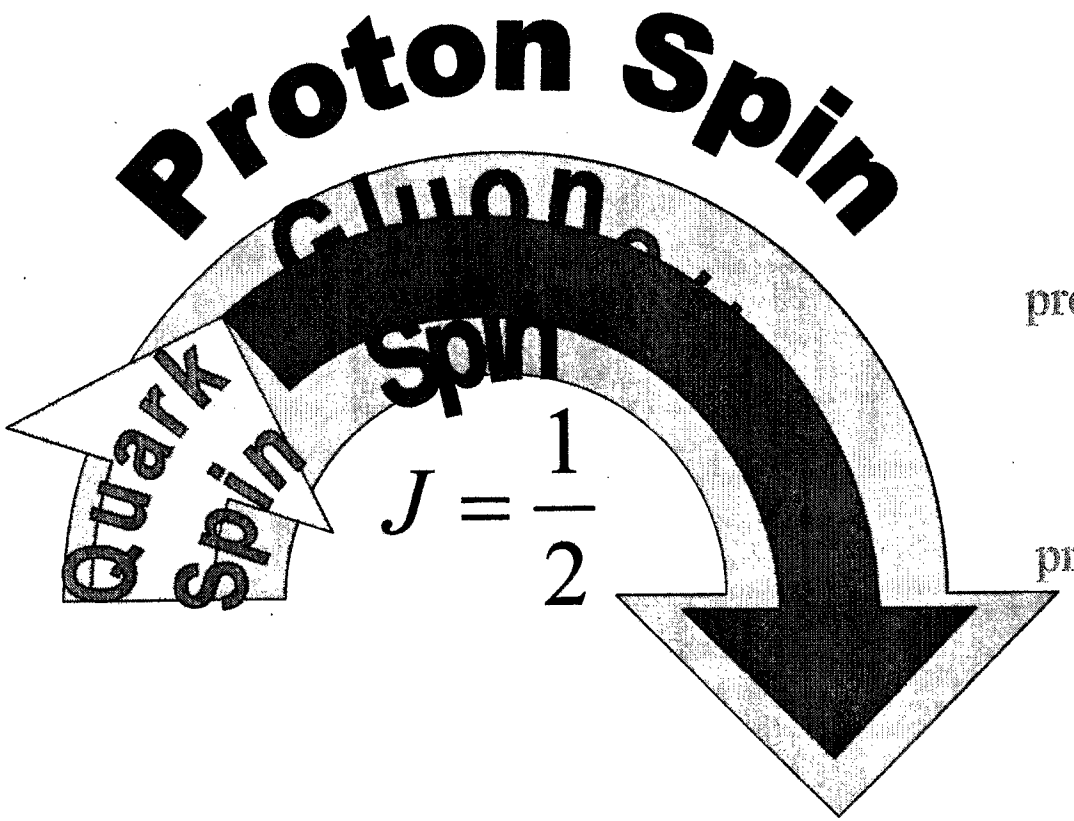
RIKEN/Wako
Masahiro Okamura
Kiyoshi Tanida
Atsushi Taketani
Rykov Vladimir
Junji. Tojo
Hisa Torii
Yoshiyuki Onuki
Hiroyuki Kano
Nobuyuki Kamihara
Kohei Fujiwara
Yasuyoshi Inoue
Hiroki Kanoh
Takuma Horaguchi

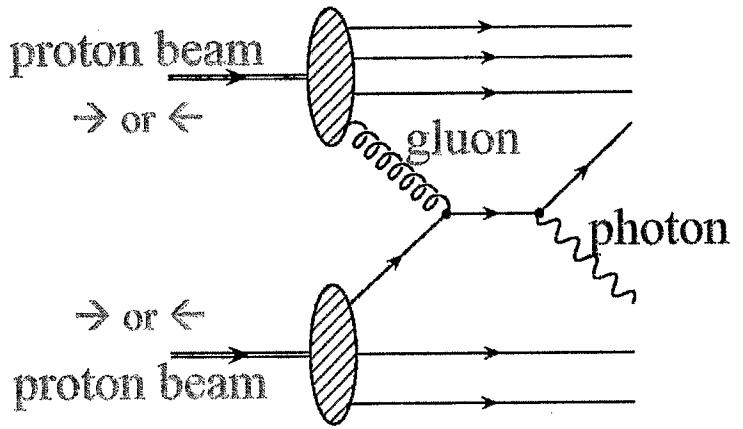
RIKEN@RBRC
Yasuyuki Akiba
Yuji Goto
Itaru Nakagawa
Tsuguchika Tabaru
Junkichi Asai
Takuma Horaguchi
Manabu Togawa
Yoshi Fukao
Hiromi Okada
K. Aoki
K. Nakano
J. Takano
K. Shoji
Y. Tsuchimoto
F. Kajihara

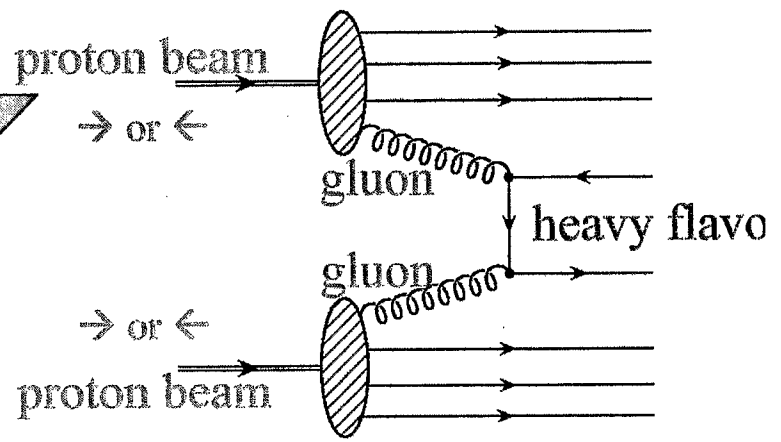
WAKO/CCJ
Takashi Ichihara
Yasushi Watanabe
Satoshi Yokkaichi
Soichiro Kametani

Students, Open-posts

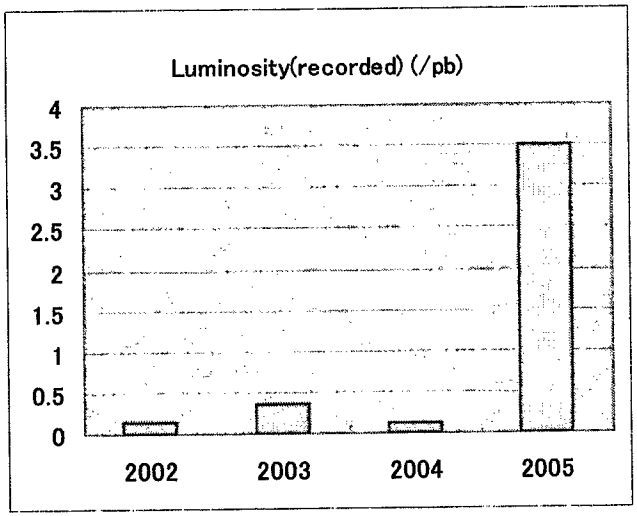
What is the fly wheel in the proton

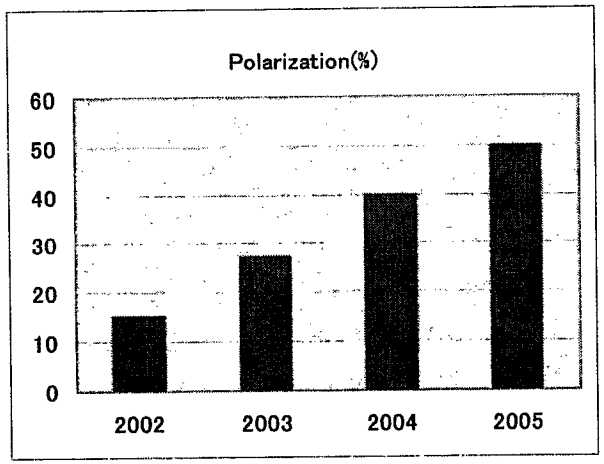






Proton Spin Crisis



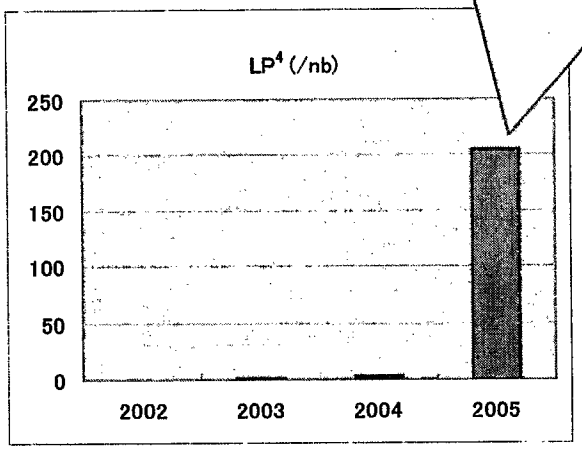


2005

First long longitudinal-spin polarized-proton run

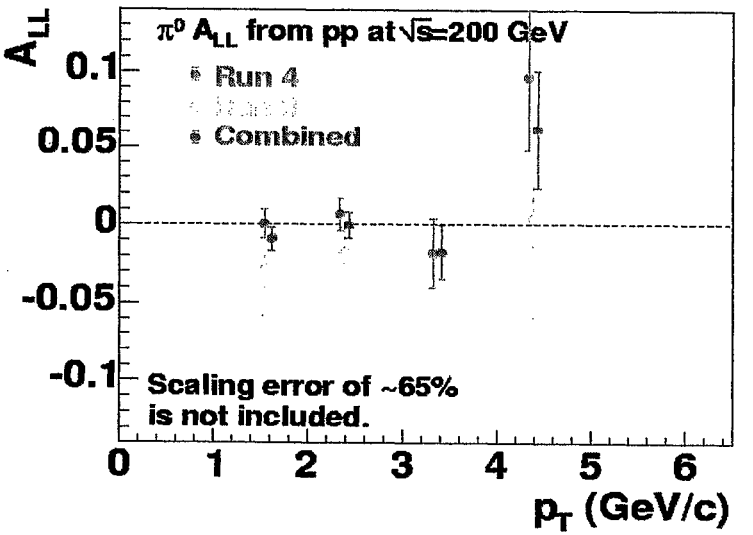
Figure of merit (LP4) more than <u>40</u> times larger than that of previous runs

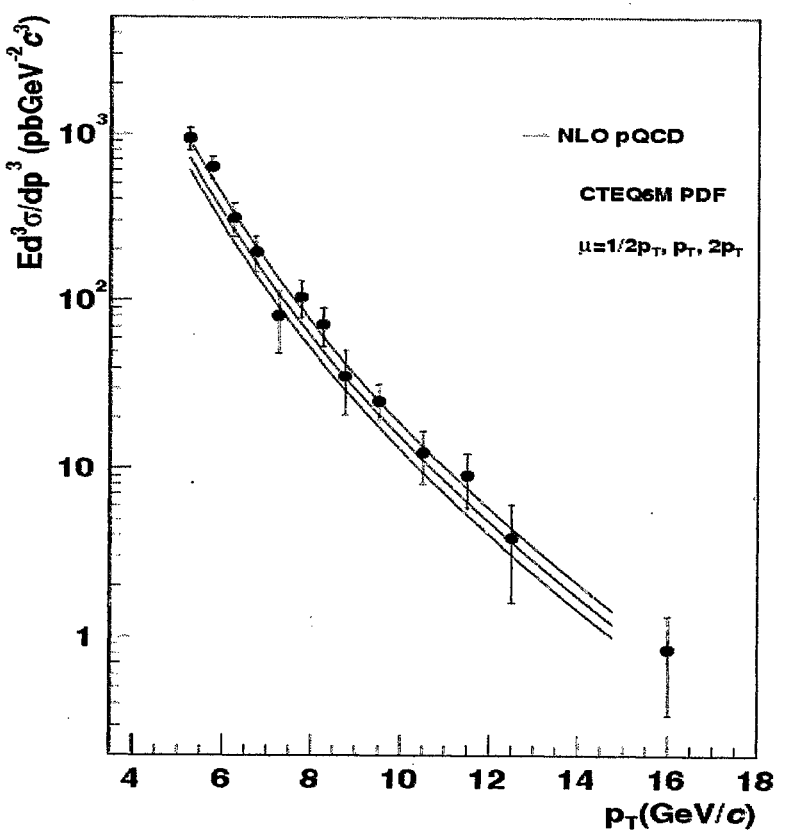
Spin Fest : Y. Goto
CCJ: Y. Watanabe

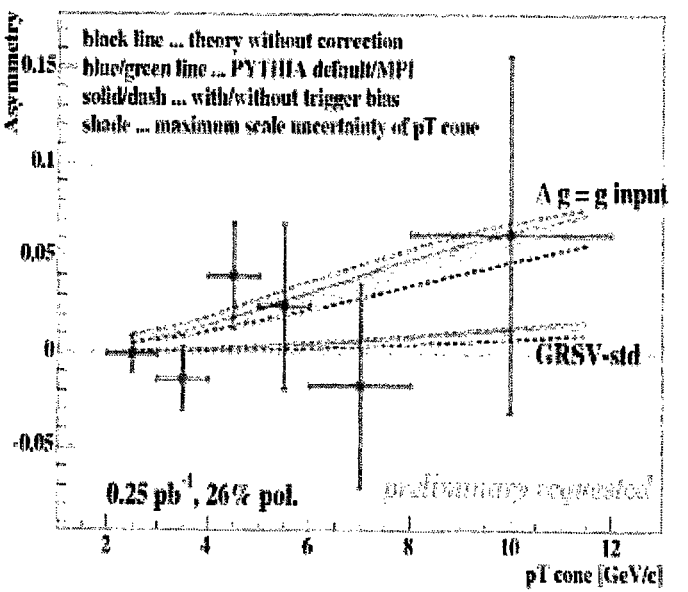


Toward Gluon Polarization

- A.Deshpande (π , Jets)
- K. Okada (Direct phton)

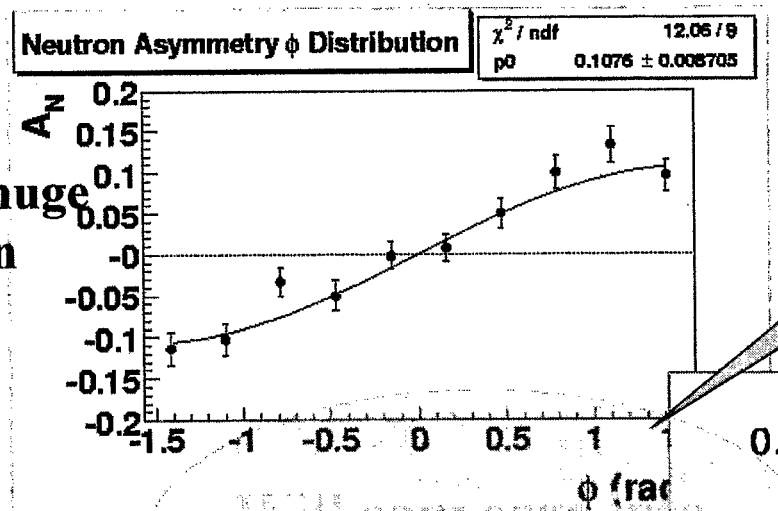






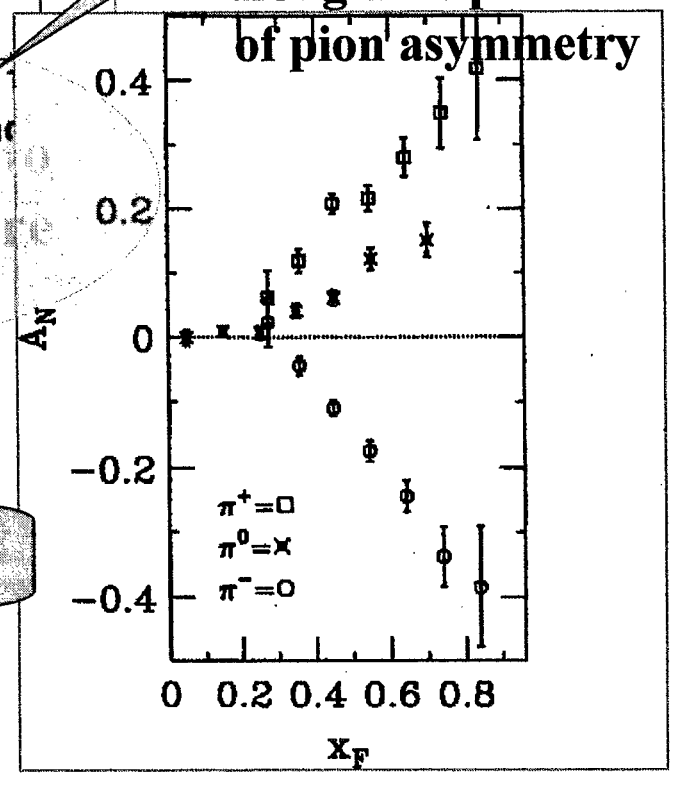
Transversity (or Orbital motion)

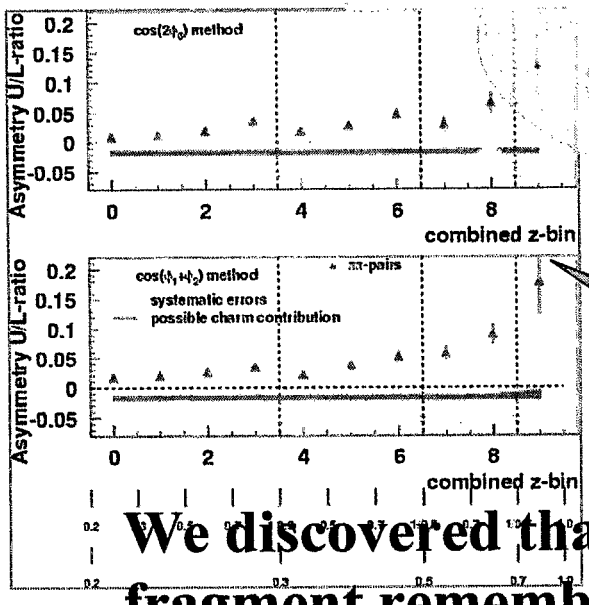
We discovered huge forward neutron asymmetry



D. Fields

Long time puzzle of pion asymmetry



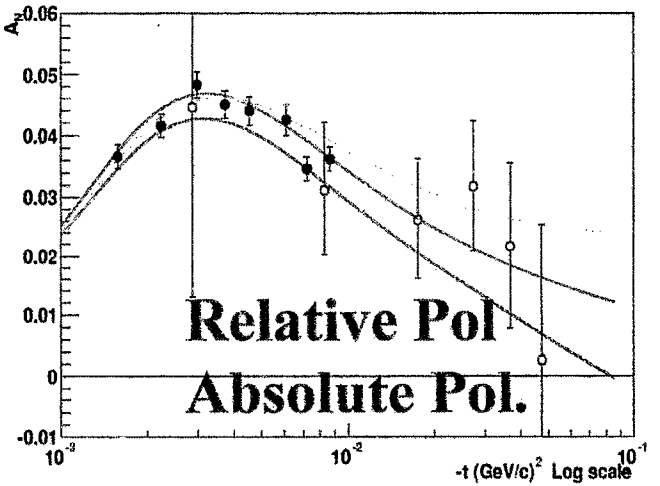


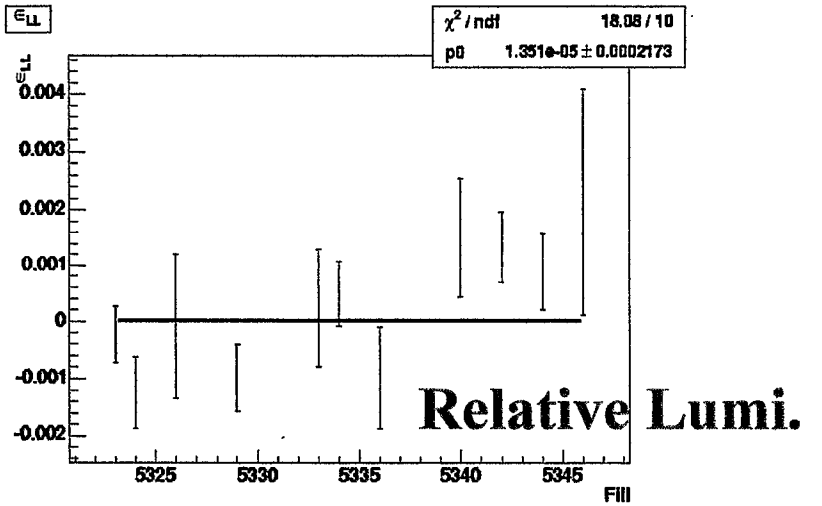
M.Perdecamp

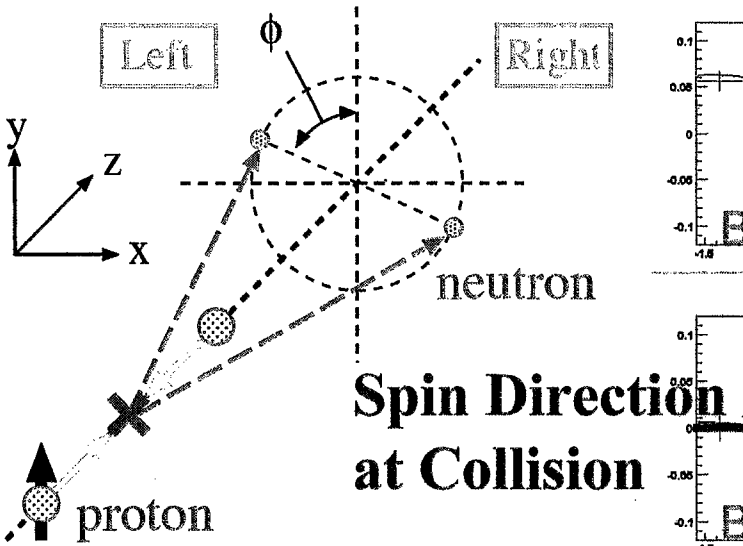
We discovered that Jet fragment remembers spin

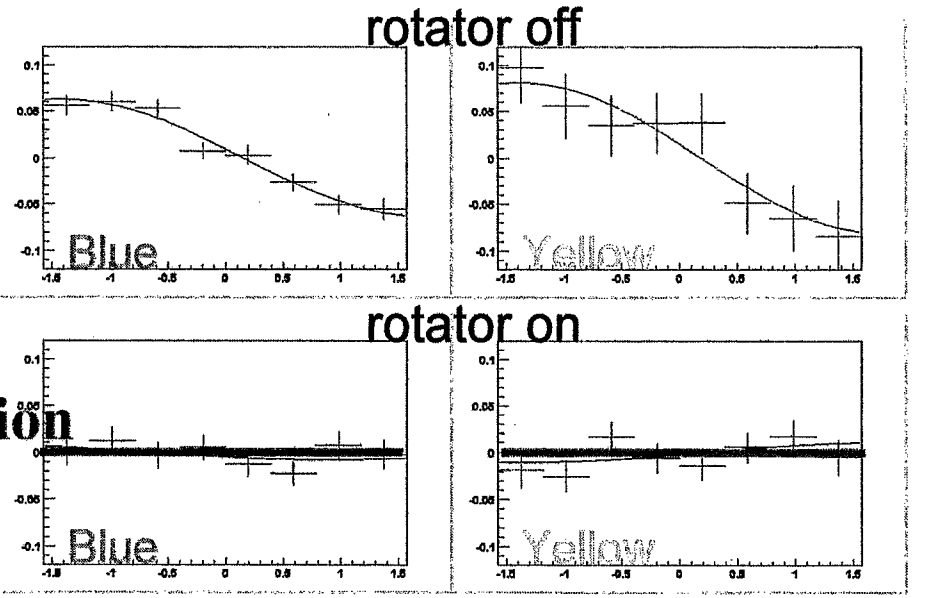
Beam Polarization and Relative Luminosity

I. Nakagwa, D.Kawall

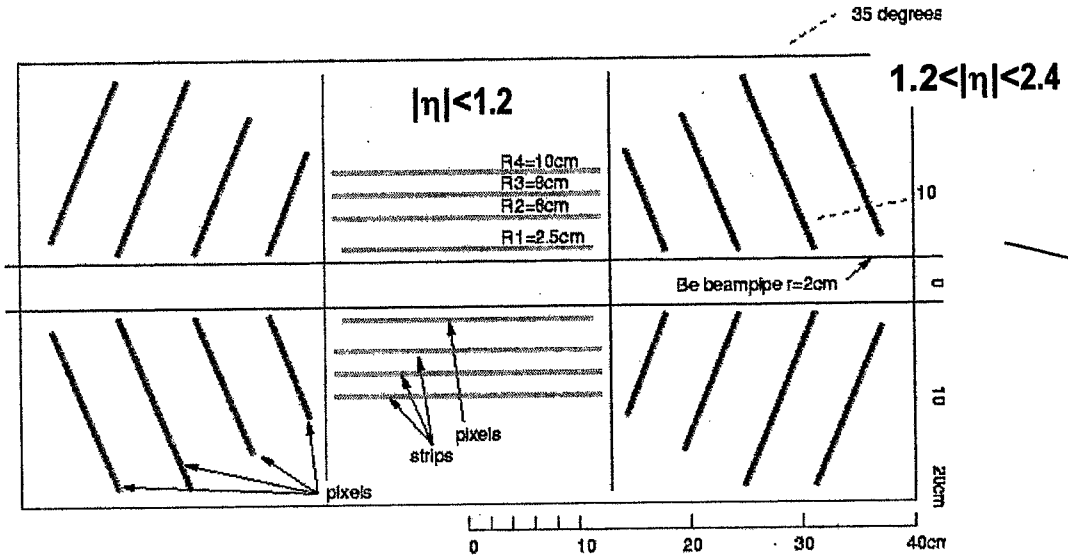


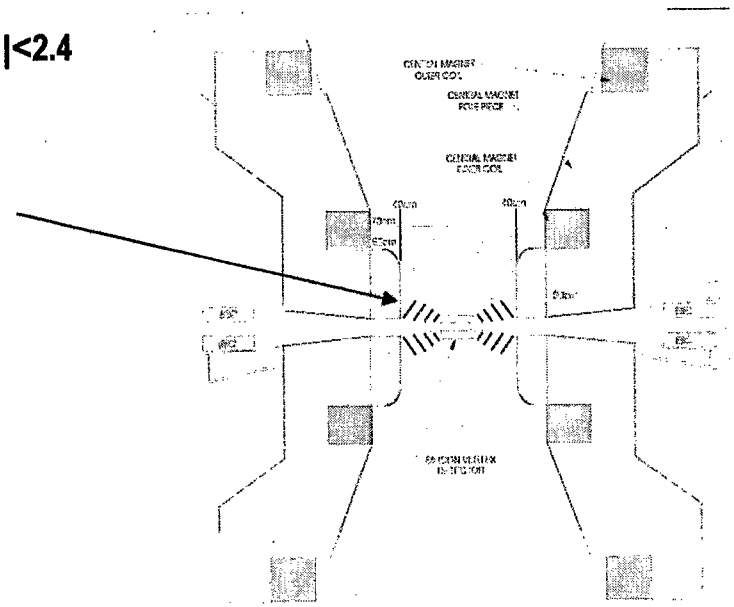






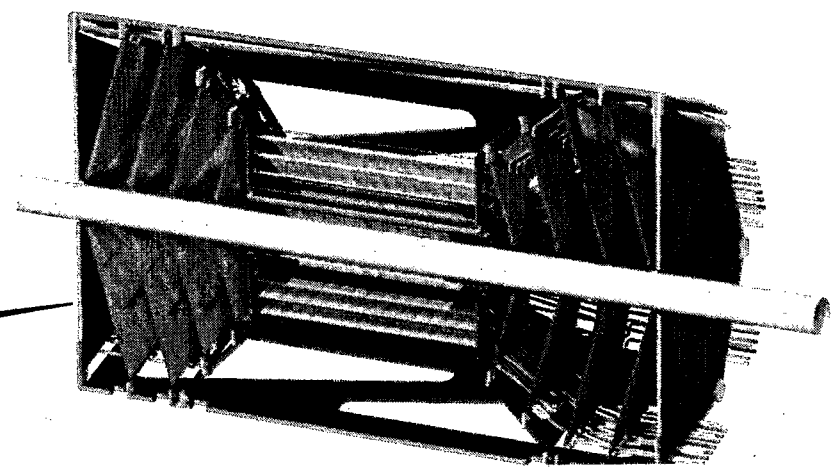
Detector Upgrade in PHENIX





Pixel barrels **(50 μm x 425 μm)**
Strip barrels **(80 μm x 3 cm)**
[illegible] **(50 μm x 2 mm)**

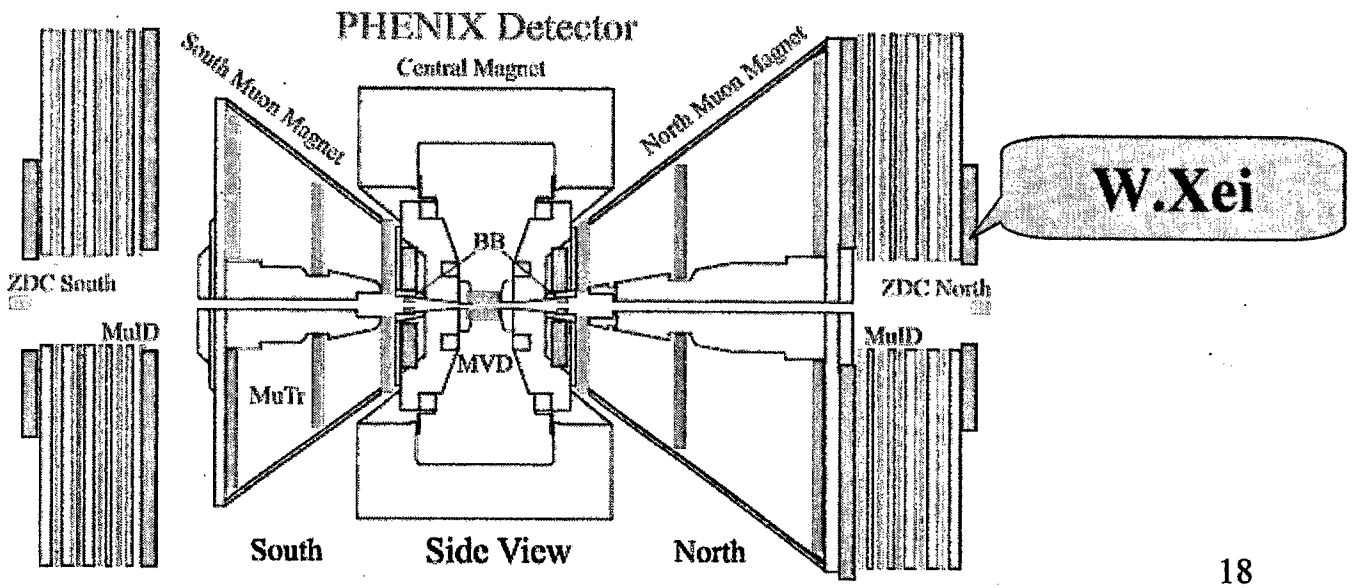
1 - 2% X_0 per layer
barrel resolution < 50 μm
endcap resolution < 150 μm



A. Taketani

Muon-trigger upgrade

- Requirement towards the $\sqrt{s}$ = 500 GeV run
- Resistive Plate Chamber technology chosen by PHENIX
  - cheap – wide coverage possible
  - can leverage existing RPC R&D from CMS
  - timing information
  - 3-dim space point for enhanced pattern recognition
- Two small prototypes successfully tested in 2005 run
- Approved NSF-MRI -- 1st Arm in 2008, 2nd Arm in 2009



Trigger RPC Locations

The world first Polarized Collider
is now producing Exciting Physics Results

We are in full swing
and will continue to be

Theoretical Physics at RIKEN BNL Research Center
Strong Interactions and QCD

Larry McLerran

Theoretical Physics at RIKEN-BNL Center

Strong Interactions and QCD

How are strongly interacting particles made from fundamental constituents?

How do fundamental interactions of QCD produce mass and confinement?

What is the behavior of strongly interacting matter in bulk?
Nuclear Matter $\longrightarrow$ Quark Gluon Plasma

What is the physics beyond the standard model?
Tests of CKM matrix.

All issues intertwined!
Require understanding and computation.

Current Interests in RIKEN-BNL Center

Lattice Gauge Theory

Masses and matrix elements of hadrons
CKM matrix
Properties of QGP and hadronic matter

Structure of Hadrons

Origin of spin
Quark and gluon distribution functions
Perturbative QCD at RHIC and LHC

Color Glass Condensate and Quark Gluon Plasma

RHIC Phenomenology
Everything for
$x \leq 10^{-2}$

Accomplishments and Goals of Lattice Gauge Theory at RBRC

Have built and are now operating QCDOC. (Two other machine built and operating: DOE and Edinburgh)

Will here preliminary results from QCDOC on

The weak interactions in strongly interacting particles

CP violation in kaon decays

Spectra of exotic hadronic states, such as pentaquark

Low energy matrix elements

QCD Thermodynamics

Accomplishments and Goals in Study of Spin and Perturbative QCD

Achievements:

Developed GRSV Spin Structure Functions

Developed one set of standard structure functions used in heavy ion, dA and pp

Used GRSV for analysis at RHIC

NLO spin asymmetry in pp and gamma p->pion X (gluon spin measurement)

QCD soft gluon resummations

Single spin asymmetries in DIS and polarized pp

Goals

Extract gluon spin from RHIC experiments

Understand hard processes in larger program

Accomplishments and Goals in Study of High Energy Density Matter

Accomplishments:

Complete 3-d computations of distributions of particle produced in heavy ion collisions and relation to QGP

Developed a theory of matter at small x: Color Glass Condensate

Understood initial conditions in heavy ion collisions and early stages of evolution

Goals:

Turn study of high energy density matter into a precise science

Understand from first principles in QCD, the high energy limit

Why is BNL a Good Place to Study QCD?

RHIC
QCDOC

Strong theory groups:
BNL, Columbia, Stony Brook

In both HEP and NP at BNL strong interest in theory and experiment
New BNL lattice gauge theory group under Karsch

Supportive atmosphere for young people

Relations

QCDOC and Lattice Gauge Theory

Joint Columbia-RBRC Project
NT has Jung as Junior Faculty
Karsch is head of lattice group
(Petreczky joint with RBRC)
Soni and Creutz
SCIDAC project

Spin and pQCD

Vogelsang is tenured
Kretzer a joint PD with NT
Larry Trueman in HEP

RHIC Physics

Strong collaboration with NT group

RIKEN-BNL Theoretical Physics Fellows

Graduates

D. Bodeker, Tenured C4, Bielefeld
D. Kharzeev ,, Tenured BNL
D. Rishke, Tenured C-4 Frankfurt
D. Son, Tenured U of Washington
R. Venugopalan, Tenured BNL
T. Wettig, Tenured C-3 Regensburg
M. Stephanov Tenured U of Ill, Chicago
U. Van Kolck, Tenured U of Arizona
T. Schaefer, Tenured U of N. Carolina
A. Kusenko, Tenured UCLA
W. Vogelsang, Tenured at BNL

New Fellows:

D. Molnar: Purdue

K. Tuchin: Iowa State

U. Weidemann Stony Brook

Current Fellows

S. Bass, Duke
T. Izubuchi, Kanazawa
S. Jeon, McGill
T. Blum, U of Connecticut
P. Petreczky, BNL (NT)
S. Sasaki, Tokyo (NT)
S. Aoki, Tsukuba
K. Iida (NT)

Next Year:

Texas A&M
Penn State U.
Minnesota?
UCLA?.....

RBRC Postdoctoral Fellows:

Spin:

S. Kretzer

F. Yuan

H. Yokoya

High Density Matter-Phenomenology

Y. Hatta

T. Doi

K. Fukushima

K. Iida

T. Sugihara

A. Mocsy

Lattice:

S. Ohta

Y. Nemoto, J. Noaki, N. Yamada, T. Yamazaki

K. Hashimoto

THEORY PRESENTATIONS

Calculations of Cross Sections and Spin Asymmetries in Hadronic Scattering

Werner Vogelsang

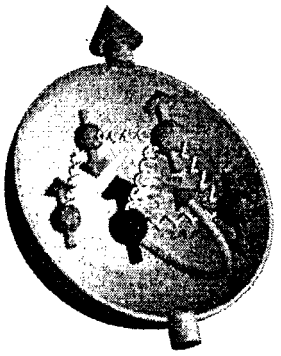
Calculations of cross sections and spin asymmetries in hadronic scattering

Werner Vogelsang
RBRC & BNL Nuclear Theory

RBRC Scientific Review, 10/10/2005

Exciting program with polarized protons underway at RHIC:

What carries the proton spin ?



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Quark spins — only ≈ 20 %

Gluon spins — ??

Quark and gluon orbital ang. mom. — ??

- **RHIC addresses the proton spin structure in new ways**
- **RBRC helps in major way to carry theory effort collaboration with BNL Nuclear Theory, High Energy Theory**

- **QCD spin physics theory in RBRC :**

  Feng Yuan, Stefan Kretzer, Hiroshi Yokoya (PhD 03/05), WV

- **some examples from past year :**

  * **single-transverse spin asymmetries in DIS and $p^{\uparrow}p$**

    Yuan, WV (to appear in PRD), Kouvaris, Qiu, Yuan, WV

→ * **QCD soft-gluon resummations**

    De Florian, WV PRD 71 (2005) 114004, PRD 72 (2005) 014014
    Shimizu, Sterman, Yokoya, WV PRD 71 (2005) 114007

  * **analysis of fragmentation fcts. in e^+e^- and $pp \to \pi^0 X$**

    Kretzer, Yokoya (in preparation)

  * **NLO QCD corrections to $p^{\uparrow}p^{\uparrow} \to \pi X$**

    Mukherjee, Stratmann, WV PRD 72 (2005) 034011

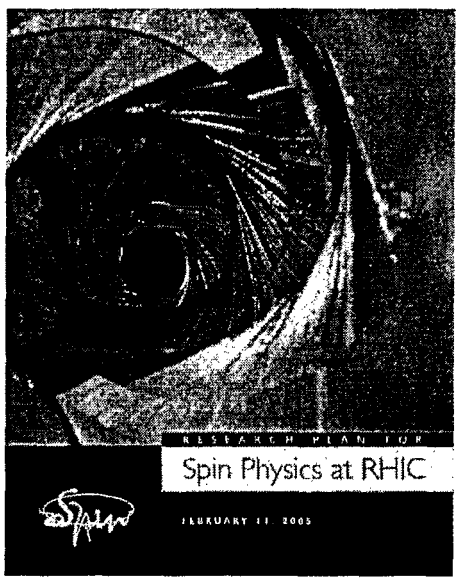
  * **NLO QCD corrections to $\vec{\gamma}\vec{p} \to \pi X$**

    Jäger, Stratmann, WV (to appear in Eur. Phys. J.)

- **"Spin plan" for DOE (02/05)**

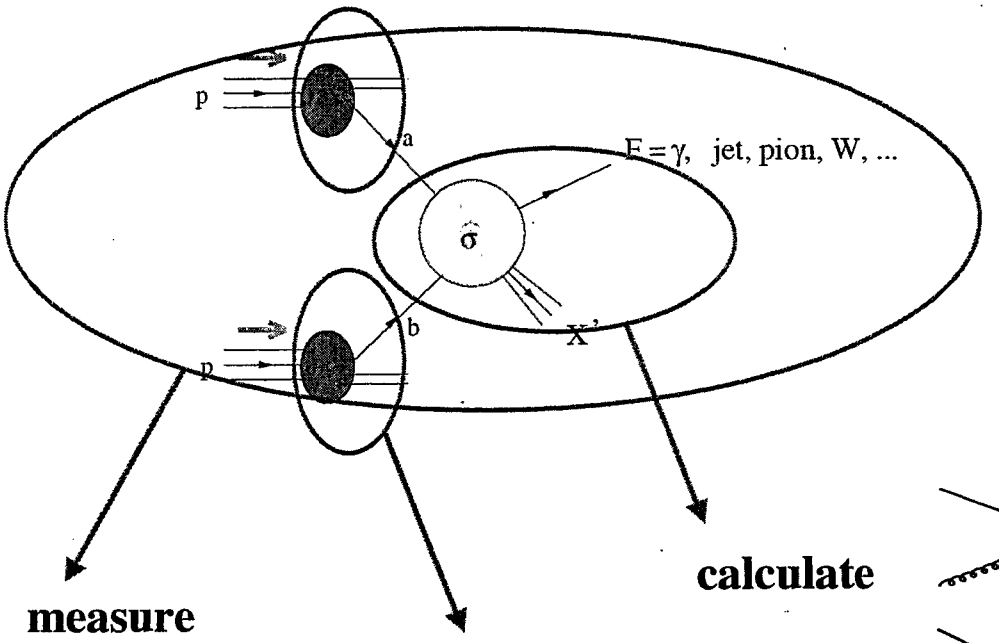
  * **reviews all plans & prospects**
    (will show some examples)

  * **major participation of RBRC members, theory & exp.**



http://spin.riken.bnl.gov/rsc/report/masterspin.pdf

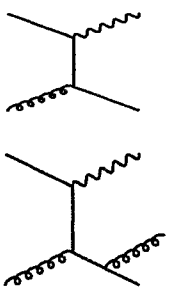
- **Review article "Study of the fundamental structure of matter with an electron-ion collider"** **A. Deshpande, R. Milner, R. Venugopalan, WV (to appear in Ann. Rev. Nucl. Part. Sci.)**



measure

calculate

→ learn about !



The calculation is the theorist's main task !
needs: precision → higher orders in QCD perturbation th.

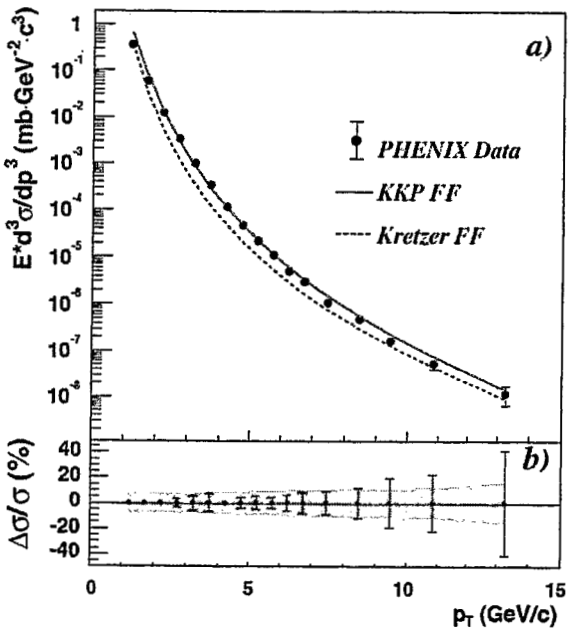
RHIC offers good possibilities to probe Δg :

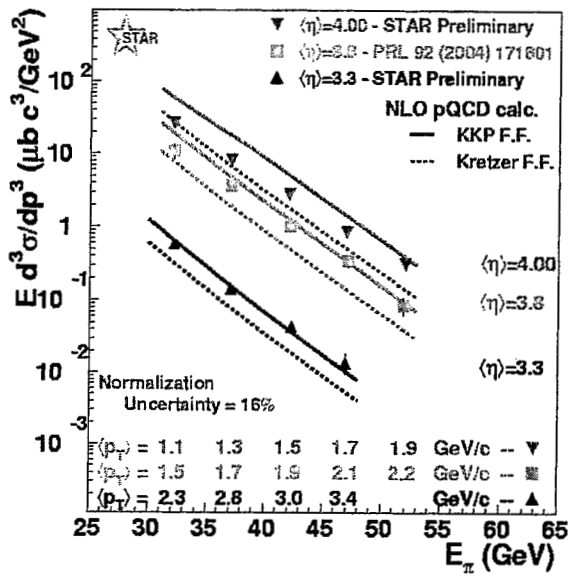
Reaction	Dom. partonic process	probes	LO Feynman diagram	
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg		Jäger, Schäfer, Stratmann, WV
$\vec{p}\vec{p} \to$ jet(s) $+ X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)	Jäger, Stratmann, WV; Signer et al.
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma +$ jet $+ X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$		Gordon, WV; Contogouris et al.: Gordon, Coriano
$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg		Stratmann, Bojak
$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$		Weber; Gehrmann; Kamal; WV
$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$ [78]	$\vec{q}\vec{\bar{q}} \to Z^0$, $\vec{q}'\vec{\bar{q}} \to W^\pm$ $\vec{q}'\bar{q} \to W^\pm$, $q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$		

NLO corrections known in all cases .

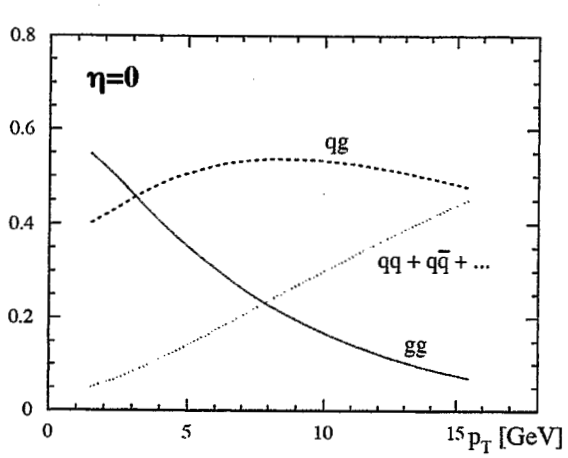
- **Calculations are already successful in unpolarized pp at RHIC:**

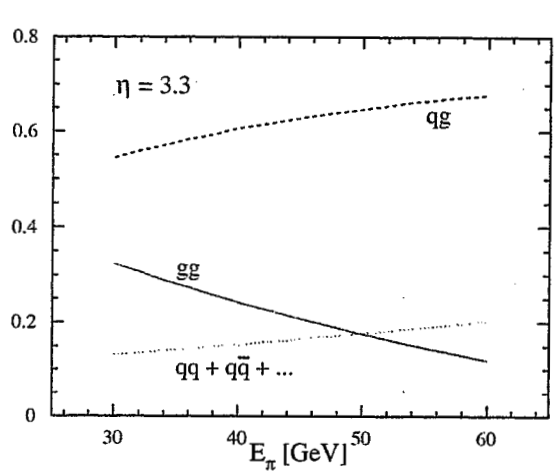
$pp \to \pi^0 X$



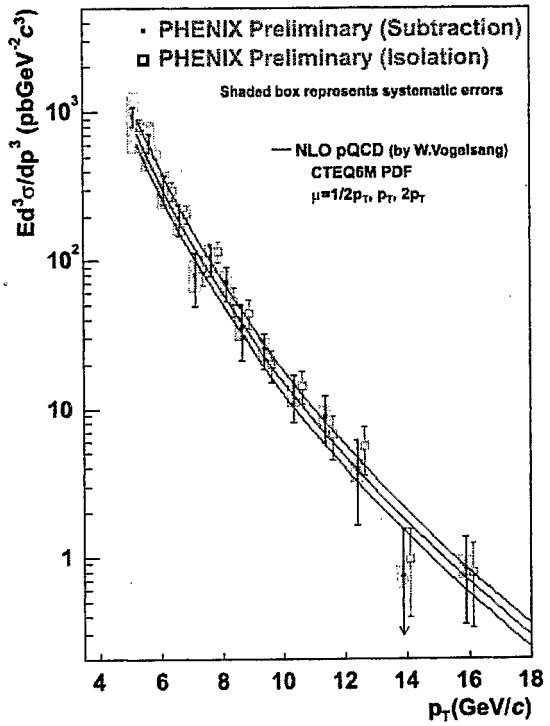


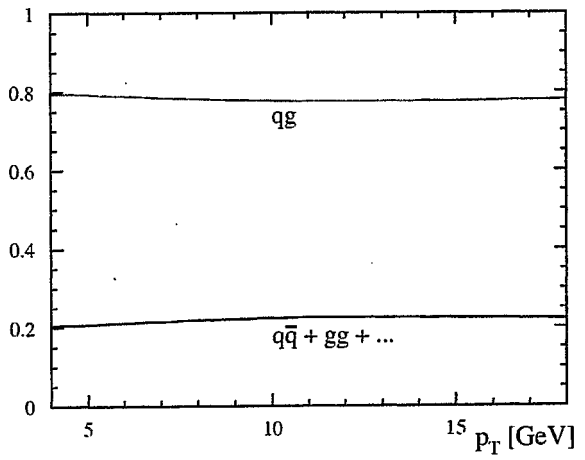
Contributions by subprocesses

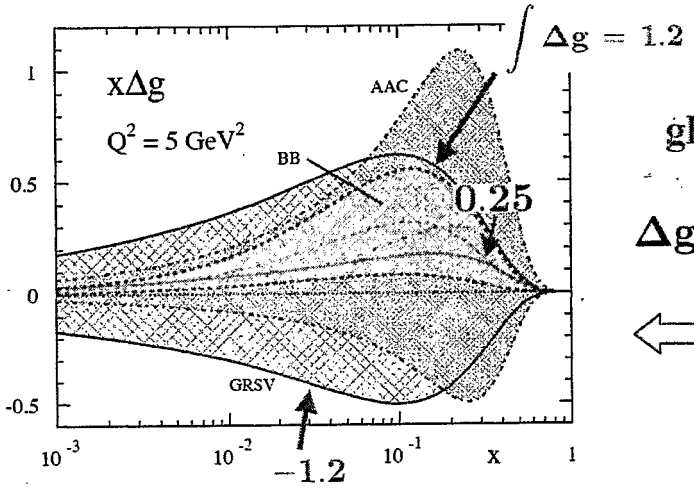




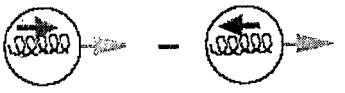
$pp \to \gamma X$





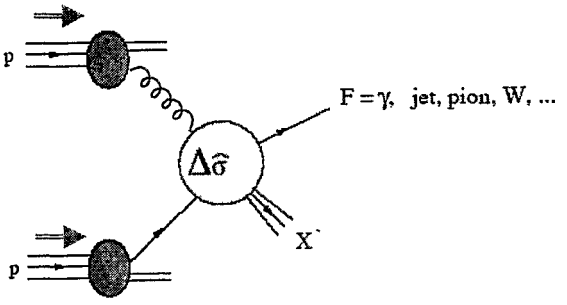


gluon polarization

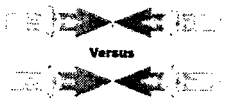
$\Delta g(x) =$ 

weak constraint from DIS scaling violations

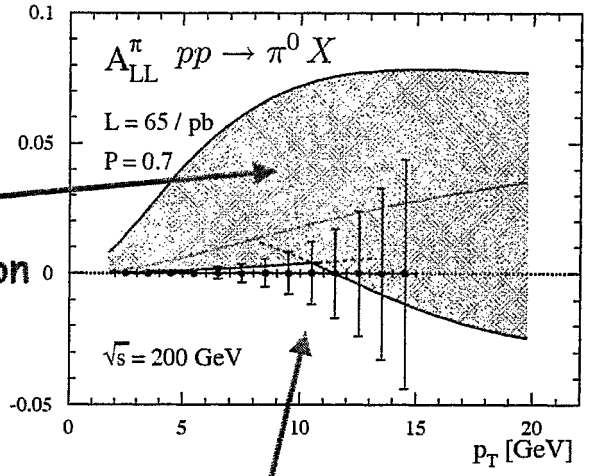
Probed by $\vec{p}\vec{p}$ collisions at RHIC !

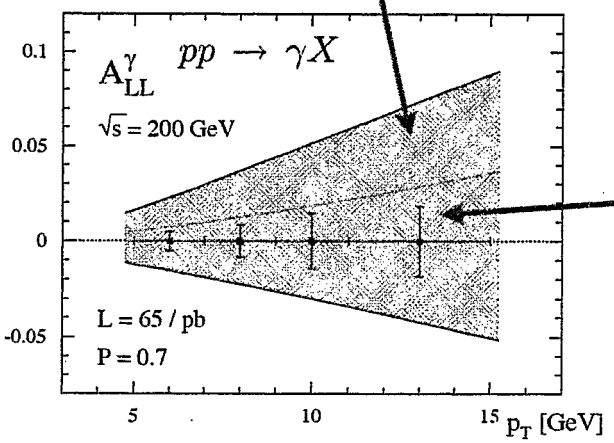


2



Due to current "uncertainty" of gluon polarization

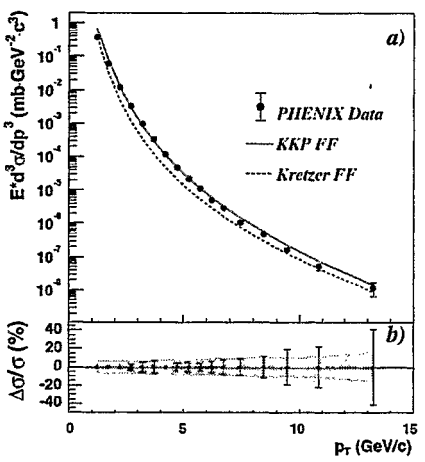


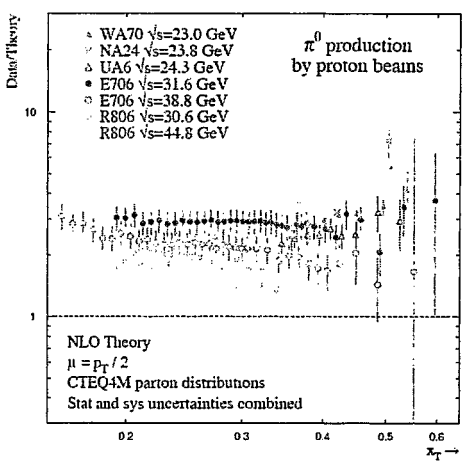


Expected RHIC stat. uncertainties

Now efforts underway for "global analysis" (Deshpande, Stratmann, Kretzer, WV, ... + CTEQ)

- **A long-standing problem :** $pp \to \pi^0 X$





...well described by NLO at RHIC

...but data much higher than NLO at fixed-target energies !

- **Detailed understanding of this issue is also important for spin physics at RHIC**

- **Resummation of important higher-order corrections beyond NLO** de Florian, WV

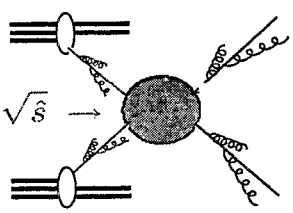
PRD 71 (2005) 114004

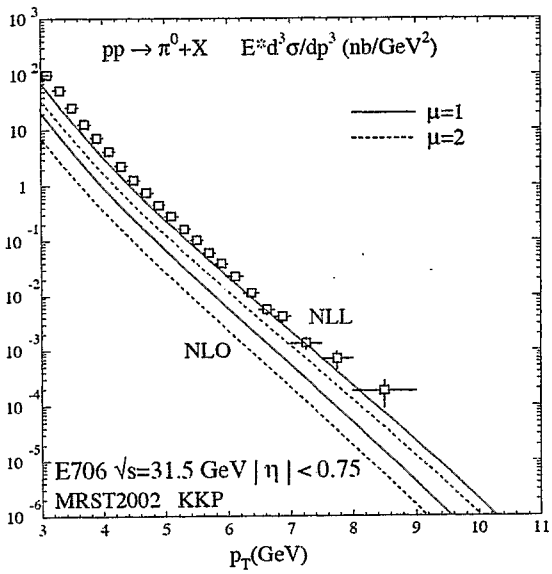
$$p_T^3 \frac{d\hat{\sigma}_{ab}}{dp_T} = p_T^3 \frac{d\hat{\sigma}_{ab}^{\rm Born}}{dp_T} \left[1 + \underbrace{\mathcal{A}_1\, \alpha_s \ln^2\left(1-\hat{x}_T^2\right) + \mathcal{B}_1\, \alpha_s \ln\left(1-\hat{x}_T^2\right)}_{\rm NLO} + \ldots + \mathcal{A}_k\, \alpha_s^k \ln^{2k}\left(1-\hat{x}_T^2\right) + \ldots \right]$$

$$\hat{x}_T \equiv \frac{2p_T}{\sqrt{\hat{s}}}$$

"threshold" logarithms

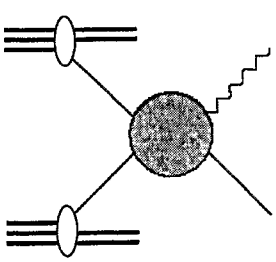
new terms lead to strong enhancement & improvement of theory vs. data →





Application to prompt photons: $pp \to \gamma X$

"direct" contributions:



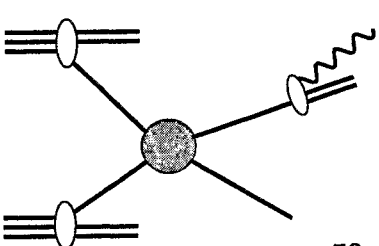
relatively small resum. effects

(Catani et al.; Sterman, WV; Kidonakis, Owens)

"fragmentation" contributions:

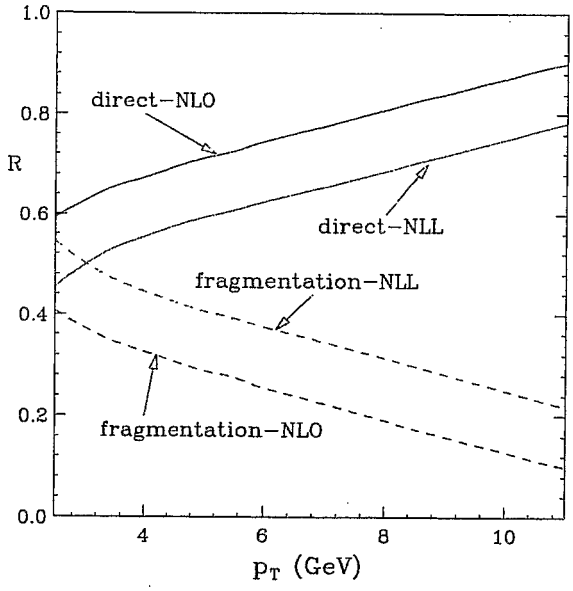
de Florian, WV

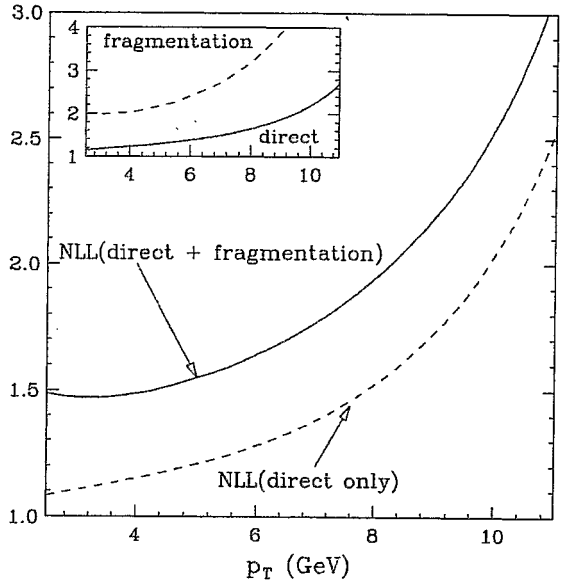
PRD 72 (2005) 014014



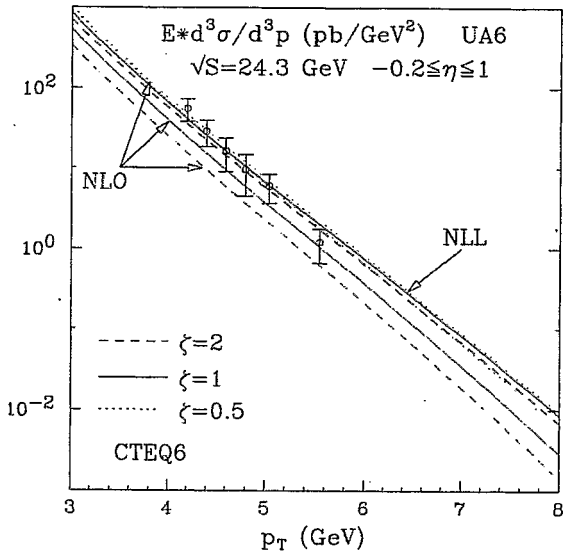
a bit like π^0 production, but less gg→gg because D_g^γ is smaller

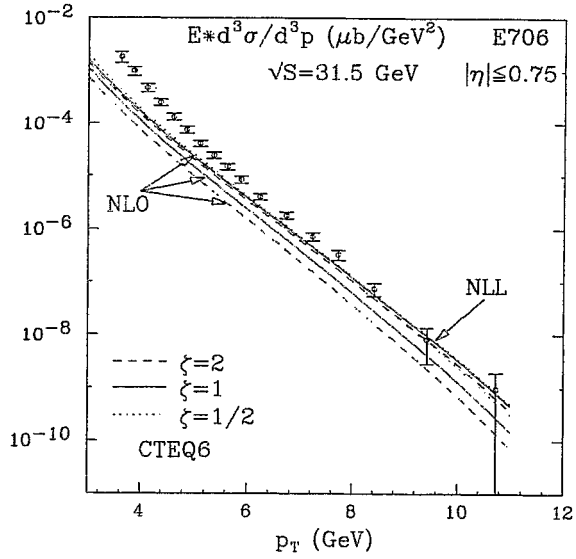
de Florian, WV





de Florian, WV





- **tremendous success of NLO at collider energies**

- **allows detailed understanding of spin asymmetries at RHIC**

- **at lower energies: resummation crucial**
  helps to achieve quantitative understanding of pion and photon spectra

Global Analysis: Update of Fragmentation Functions

Stefan Kretzer

Global Analysis:
Update of Fragmentation Functions

Stefan Kretzer

Brookhaven National Laboratory &

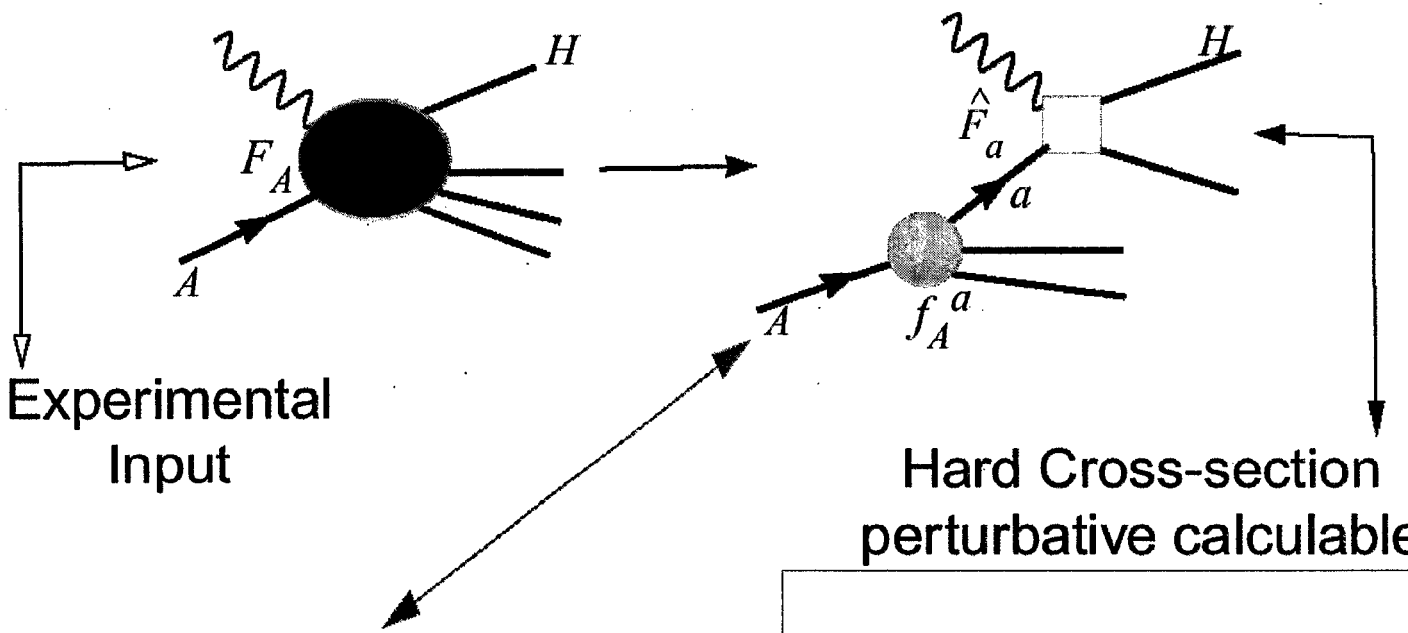
RIKEN-BNL

RBRC Scientific Review Committee Meeting
October 10, 2005

Global QCD Analysis in a Nutshell

Master Equation for QCD Parton Model – the Factorization Theorem

$$F_A^\lambda(x, \frac{m}{Q}, \frac{M}{Q}) = \sum_a f_A^a(x, \frac{m}{\mu}) \otimes \hat{F}_a^\lambda(x, \frac{Q}{\mu}, \frac{M}{Q}) + \mathcal{O}((\frac{\Lambda}{Q})^2)$$



Experimental Input

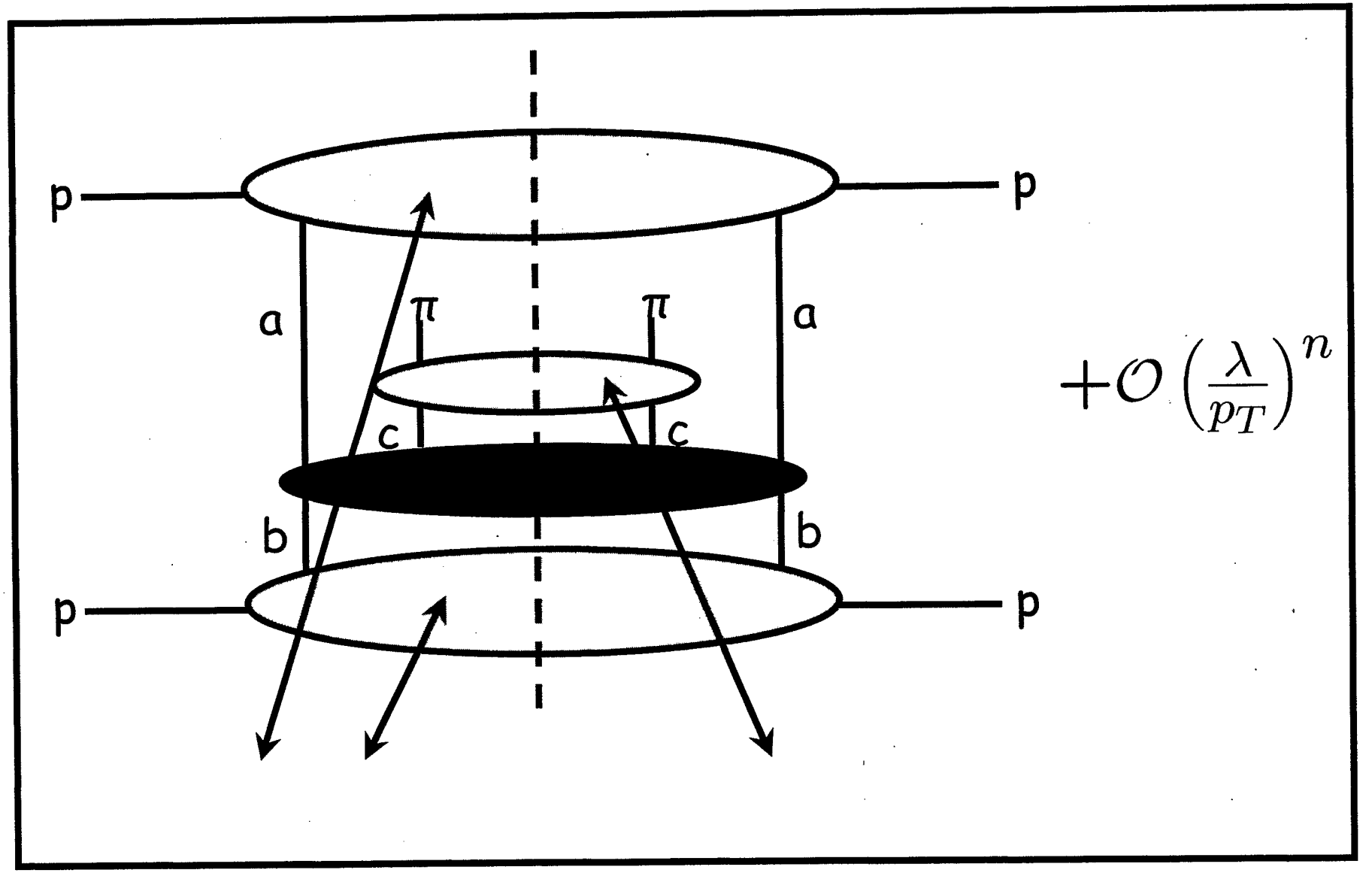
Hard Cross-section perturbative calculable

Parton Dist. Fn.

Non-Perturbative Parametrization at Q_0

DGLAP Evolution to Q

Semi-Inclusive Reactions



$$+\mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$

Hadroproduction: pp_π X at 200 GeV cms

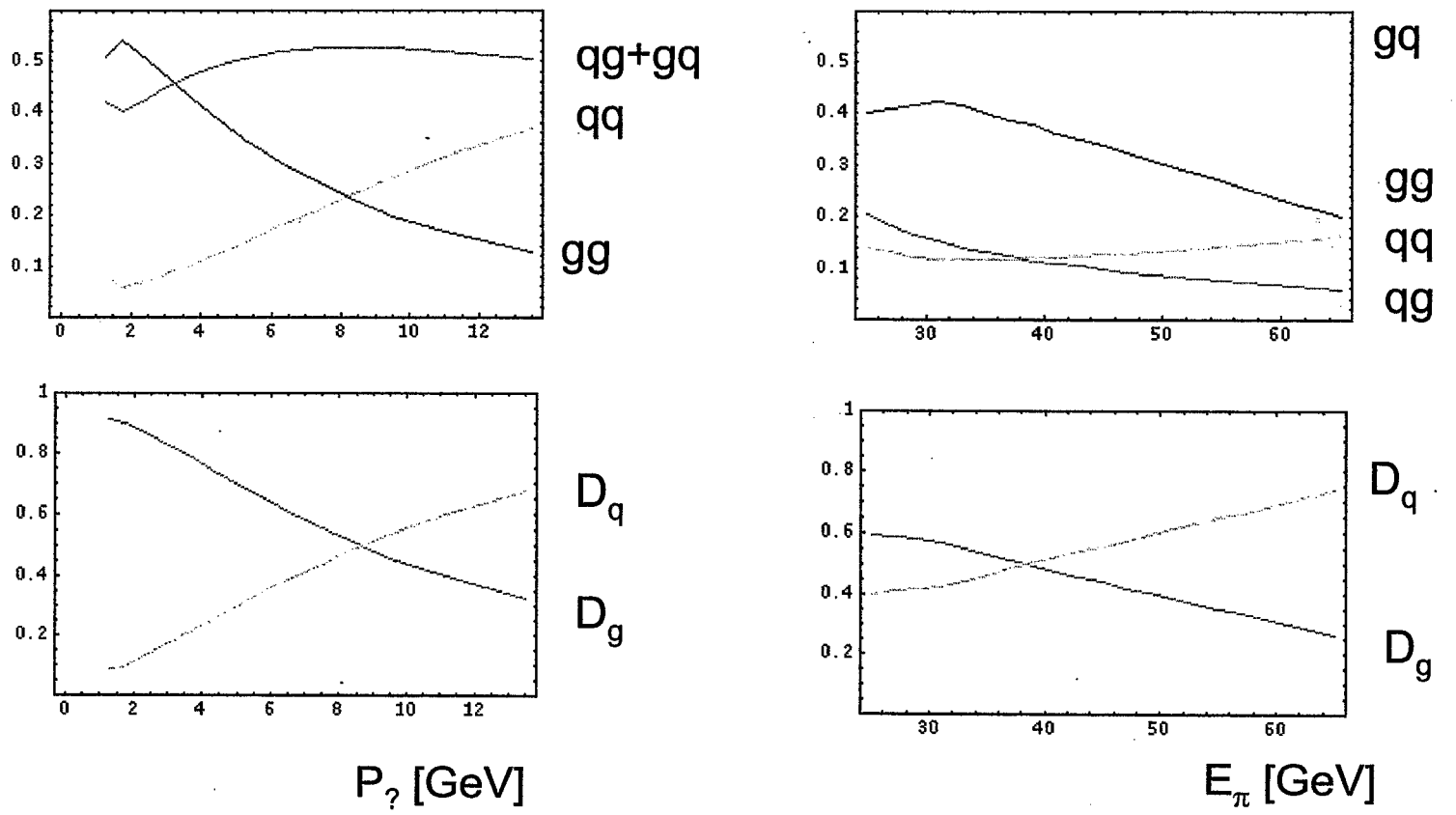
Fractional contributions from initial/final state partons

Central Rapidity

Forward Rapidity

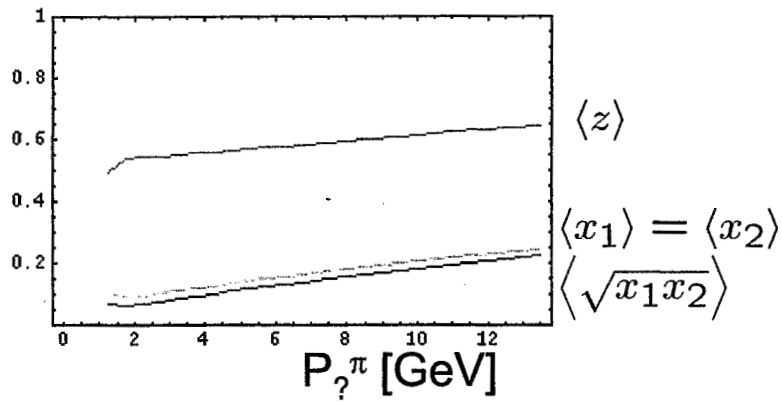
initial

final

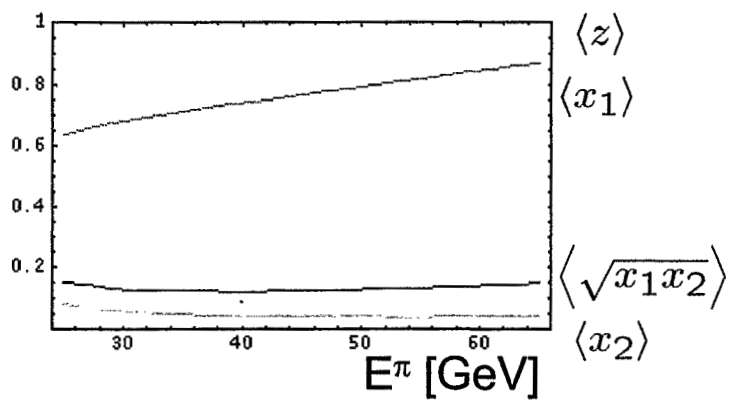


Average Scaling Variables

Central Rapidity



Forward Rapidity



- Symmetric / asymmetric kinematics for central / forward rapidity
- Large z fragmentation is probed.
- PDFs are well known in the relevant x range

Gluon Fragmentation in $b\bar{b}g$ 3-jet topologies

experimental Fragmentation Function

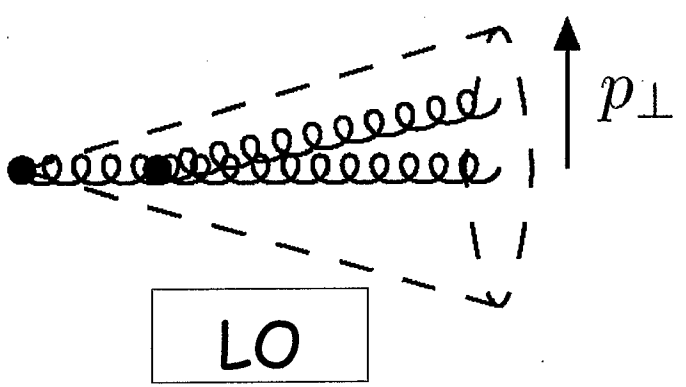
$$D_g^h(x_E, \mu^2) \equiv \frac{1}{N_{\rm tot}} \frac{\Delta N_g^h}{\Delta x_E}; \quad x_E \equiv \frac{E_h}{E_g^{\rm jet}}$$

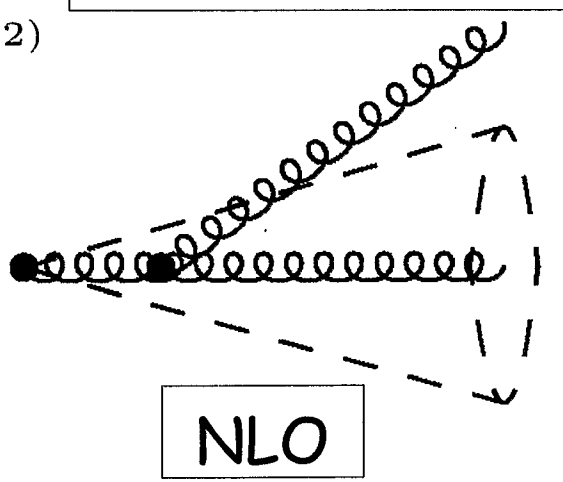
LO QCD scaling violations

$$\int_{\mu^2}^{(p_\perp^{\rm max})^2} \frac{dp_\perp^2}{p_\perp^2} \left[P_{ji}^{(0)}(z)\right]_{p_\perp=0} = P_{ji}^{(0)}(z) \ln\left(\frac{p_\perp^{\rm max}}{\mu}\right)^2$$

$$\hookrightarrow \left.\frac{dD_g^h(x_E, \mu^2)}{d\ln\mu^2}\right|_{\mu=E^{\rm jet}\sin(\theta/2)}$$

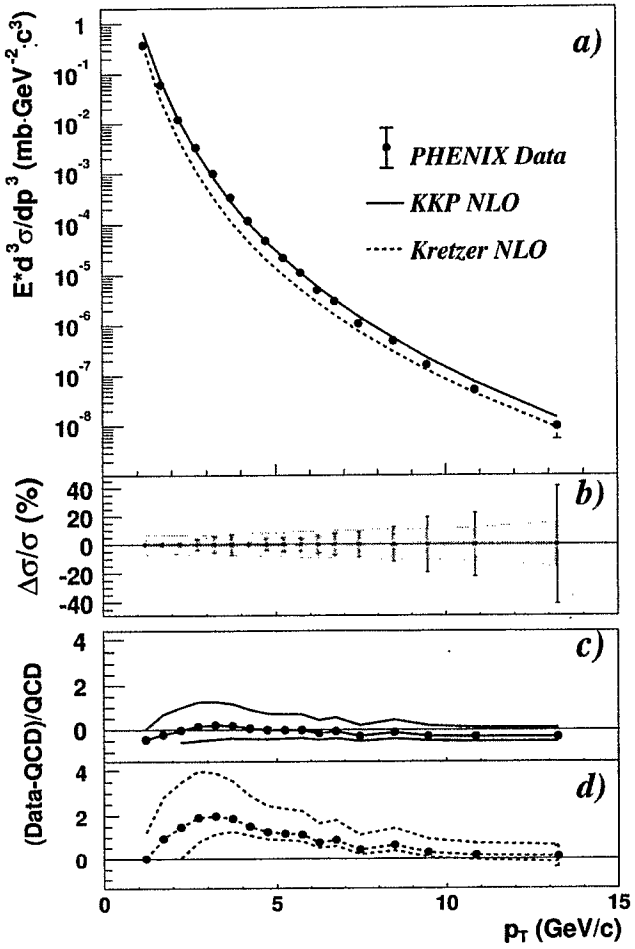
LO – DGLAP



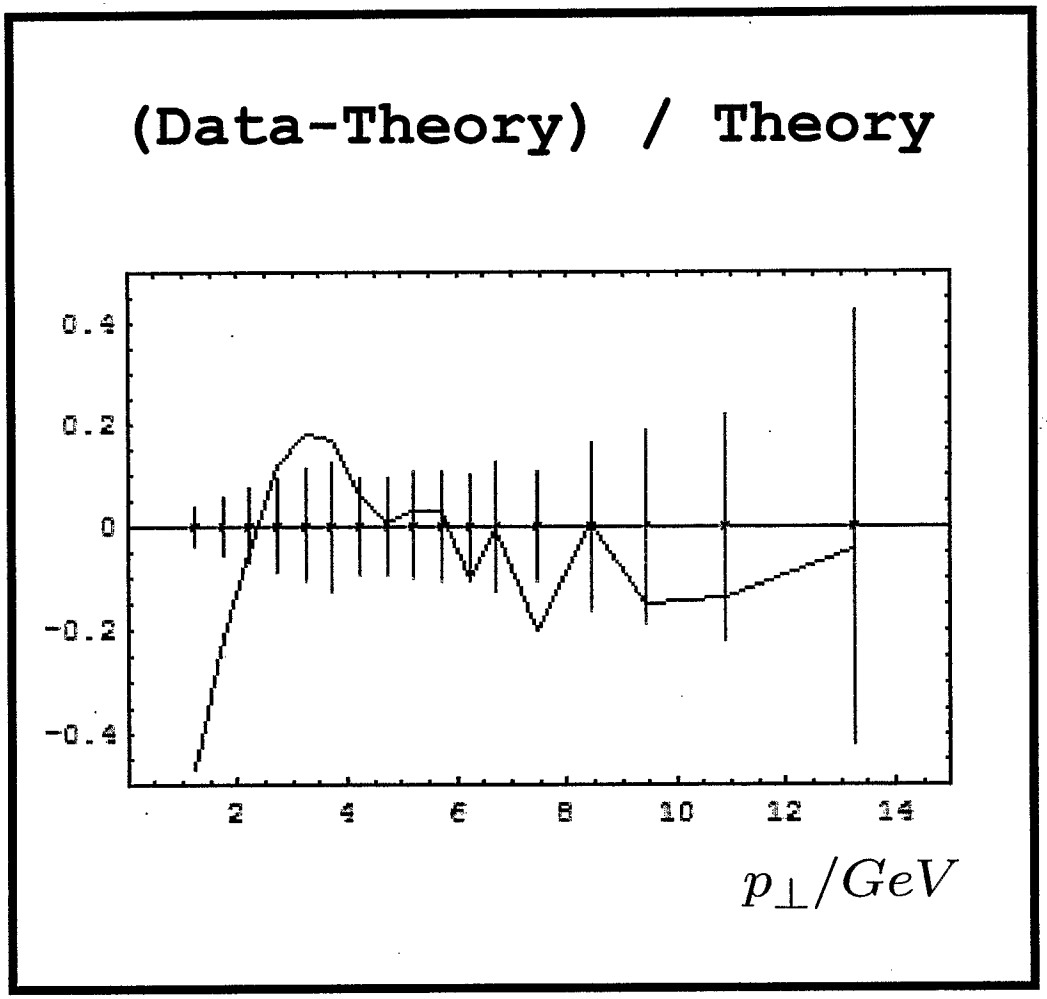


Summary

Old:

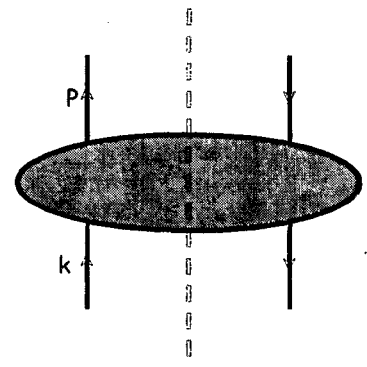


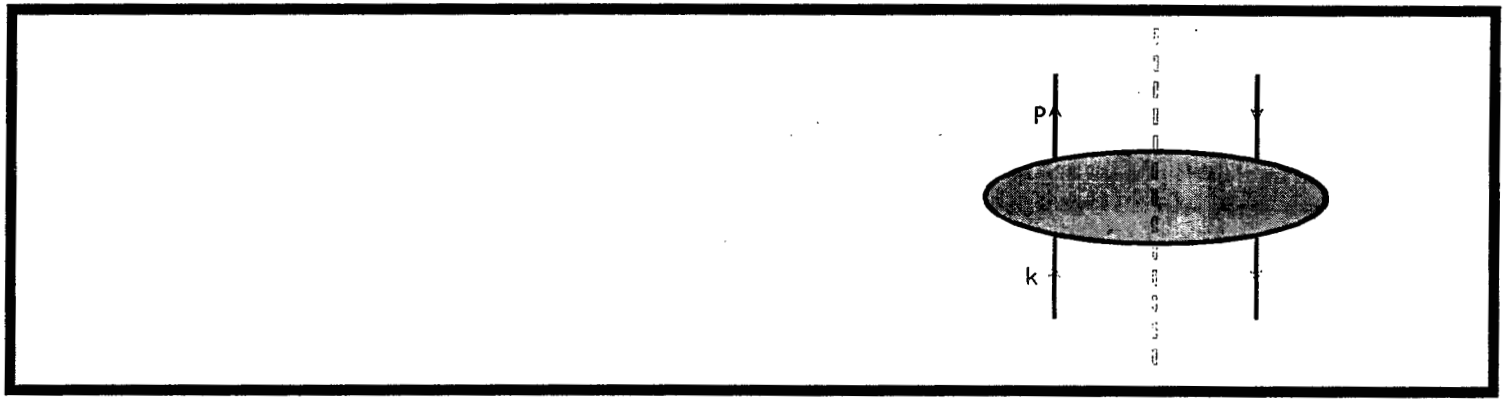
Update:



The parton model limit does not exist for fragmentation functions:

Hadron mass effects and dynamical higher twists are delicately entwined.



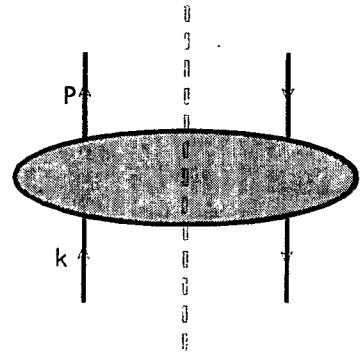


Qualitative (dual) features:

- Heavier (light) hadrons come with a harder FF. (The low scale evolution is cut-off.)

- Heavier hadrons are suppressed. (The virtual parton has to survive a multiple of its perturbative lifetime)

- Factorization will set in at larger pT for massive particles: pT >> M^2 / z !



Quantitative (order of magnitude) estimate:

$p_\perp^{2\pi} \simeq 3$ GeV

$x_1 \simeq x_2 \simeq 0.1$

$z \simeq 0.5$

And slowly approaching M_ρ with increasing $p_\perp^{2\pi}$.

Single Transverse Spin Physics--From DIS to Hadronic Collisions

Feng Yuan

(Single) Transverse Spin Physics

-- from DIS to hadronic collisions

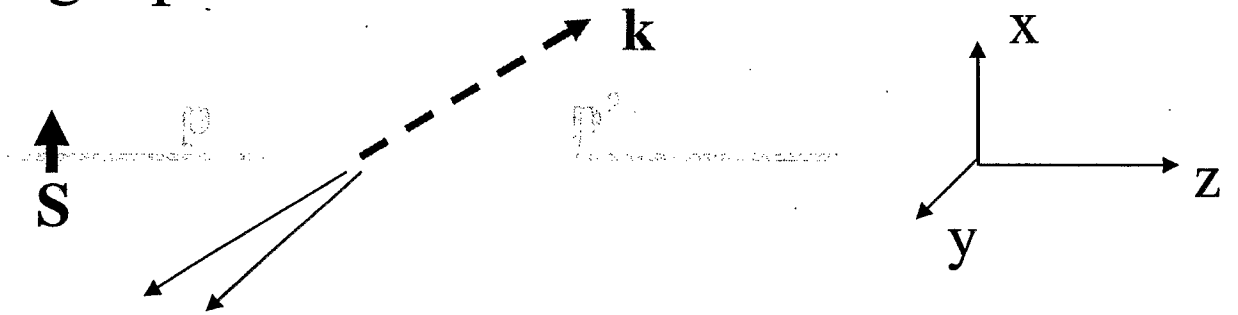
Feng Yuan

RBRC , Brookhaven National Laboratory

W. Vogelsang, F.Y. , hep-ph/0507266, to appear in PRD

What is Single Spin Asymmetry?

- Consider scattering of a transversely-polarized spin-1/2 hadron (S, p) with another hadron, observing a particle of momentum k



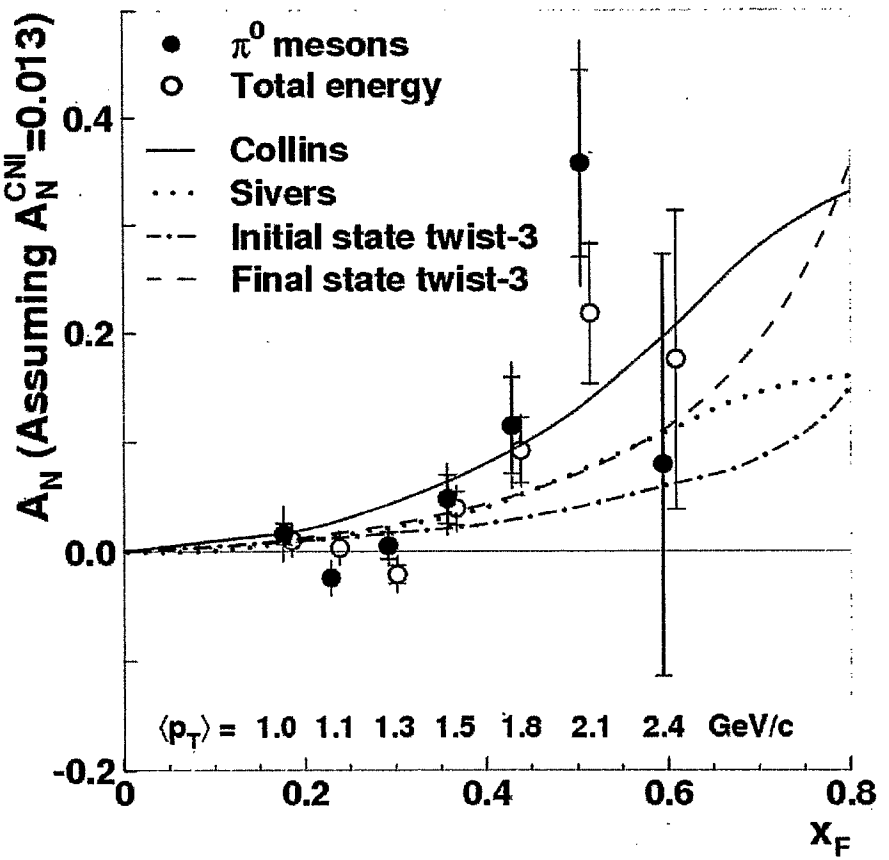
The cross section can have a term depending on the azimuthal angle of **k**

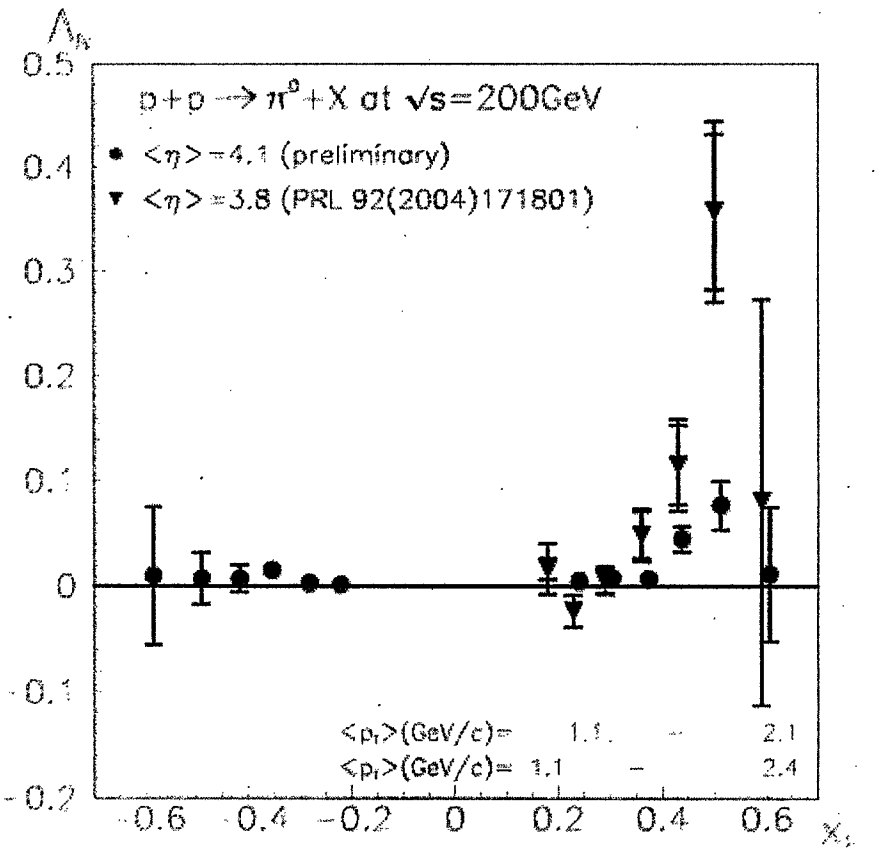
$$d\sigma \sim \vec{S} \cdot (\vec{p} \times \vec{k})$$

which produce an asymmetry A_N when S flips: **SSA**

SSA at RHIC

STAR Collaboration, Phys.Rev.Lett.92:171801,2004; hep-ex/0412035





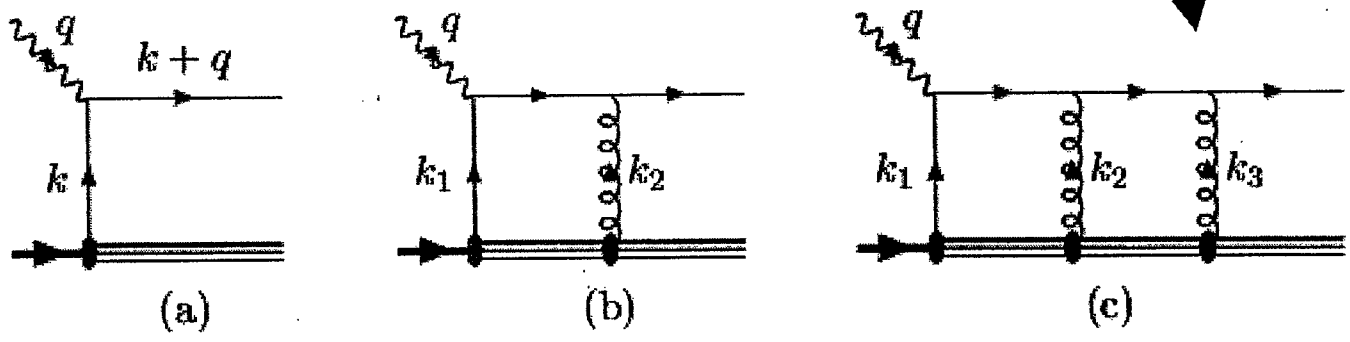
Naïve Parton Model Fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: ( )
  - The only way to generate the hadron helicity-flip is through quark helicity flip, which is proportional to current quark mass
  - To generate a phase difference, one has to have pQCD loop diagrams, proportional to
- Two ways to generate sizable SSA
  - **Transverse momentum dependent (TMD) parton distributions ( )**
  - Twist-three mechanism (Qiu-Sterman)

TMD Distribution: the definition

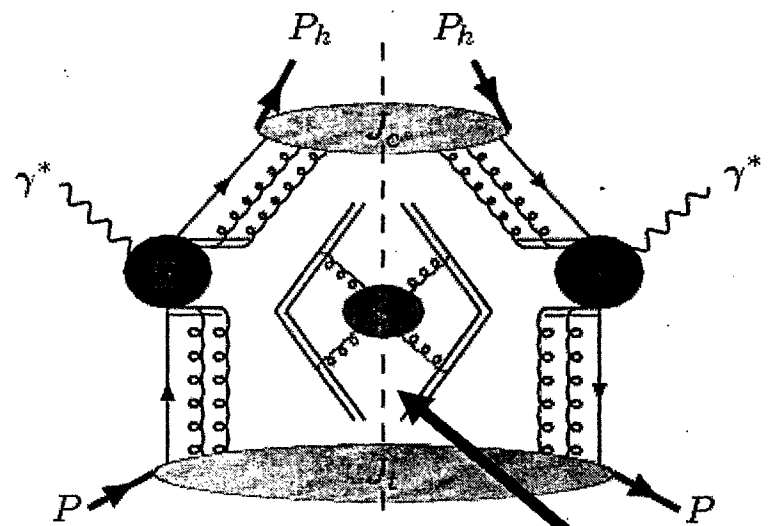
$$\mathcal{Q}(x, k_\perp, \mu, x\zeta) = \frac{1}{2}\int \frac{d\xi^-}{2\pi} e^{-ix\xi^- P^+} \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp \cdot \vec{k}_\perp}$$
$$\times \left\langle P \left| \overline{\psi}_q(\xi^-, 0, \vec{b}_\perp) \mathcal{L}_v^\dagger(\infty; \xi^-, 0, \vec{b}_\perp) \gamma^+ \mathcal{L}_v(\infty; 0) \psi_q(0) \right| P \right\rangle$$

Gauge Invariance requires the Gauge Link



Brodsky,Hwang,Schmidt 02'
Collins 02'
Belitsky,Ji,Yuan 02'

QCD Factorization



Soft Factor

$$F(x_B, z_h, P_{h\perp}, Q^2)$$
$$= \sum_{q=u,d,s,\ldots} e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\ell}_\perp$$
$$\times\, q\left(x_B, k_\perp, \mu^2, x_B\zeta, \rho\right)\widehat{q}_h\left(z_h, p_\perp, \mu^2, \widehat{\zeta}/z_h, \rho\right)S(\vec{\ell}_\perp, \mu^2, \rho)$$
$$\times\, H\left(Q^2, \mu^2, \rho\right)\delta^2(z_h\vec{k}_\perp + \vec{p}_\perp + \vec{\ell}_\perp - \vec{P}_{h\perp})$$

TMDs at RHIC

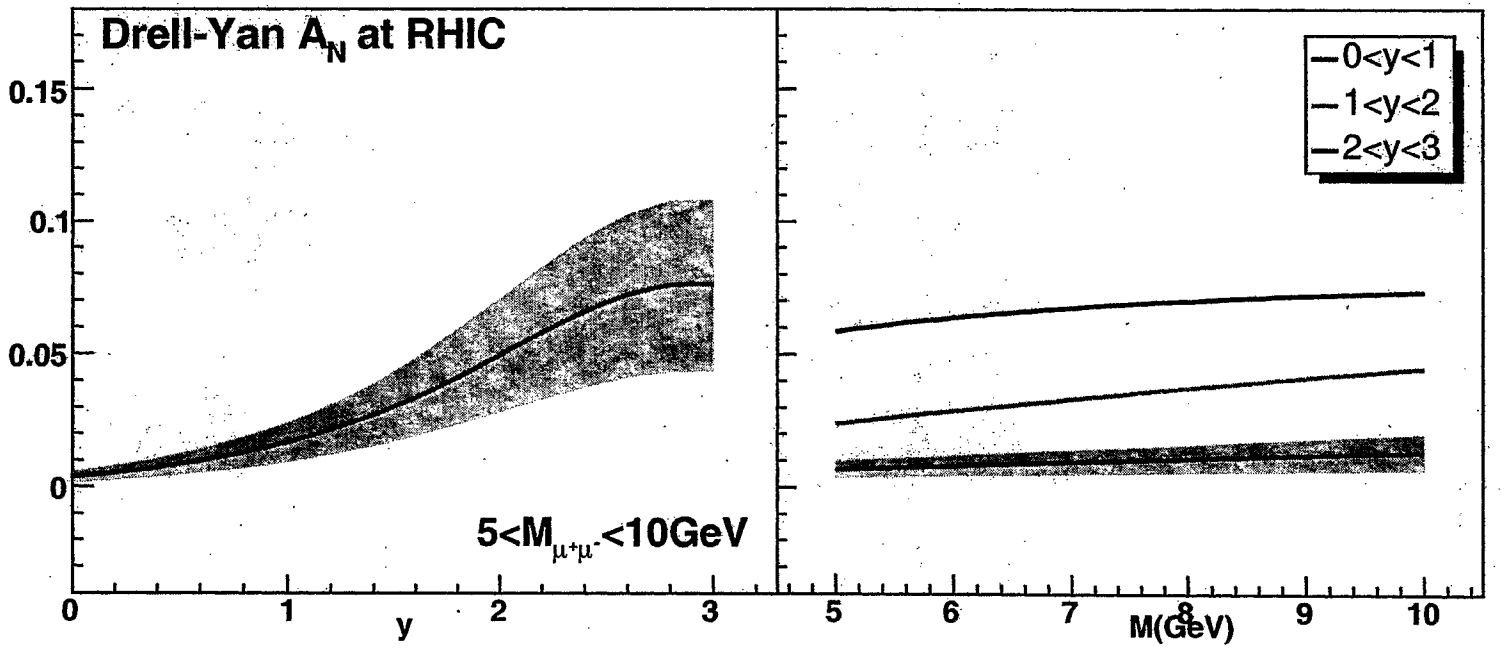
- Drell-Yan

  SSA for Drell-Yan: Sivers function has opposite sign, $q_T^{DY}=-q_T^{DIS}$, because of the gauge link changing direction.

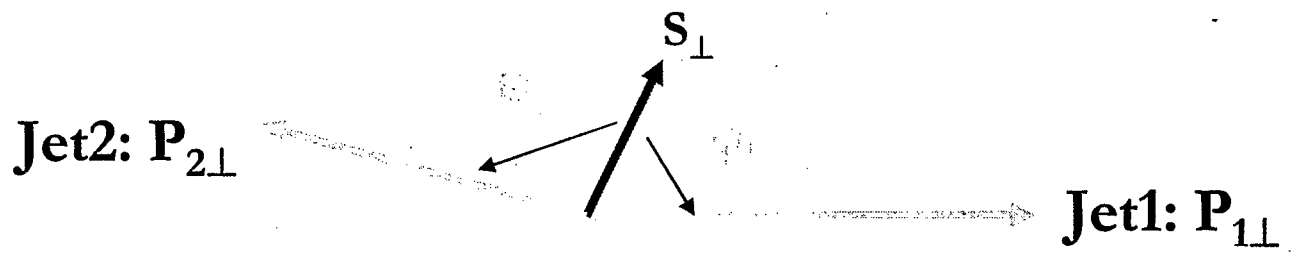
- Di-Jet Correlation

  There is no factorization proof yet. It is likely factorizable in terms of TMDs. However, the universality of Sivers function for this case is not clear yet. We assume they are the same as DY.

SSA for Drell-Yan



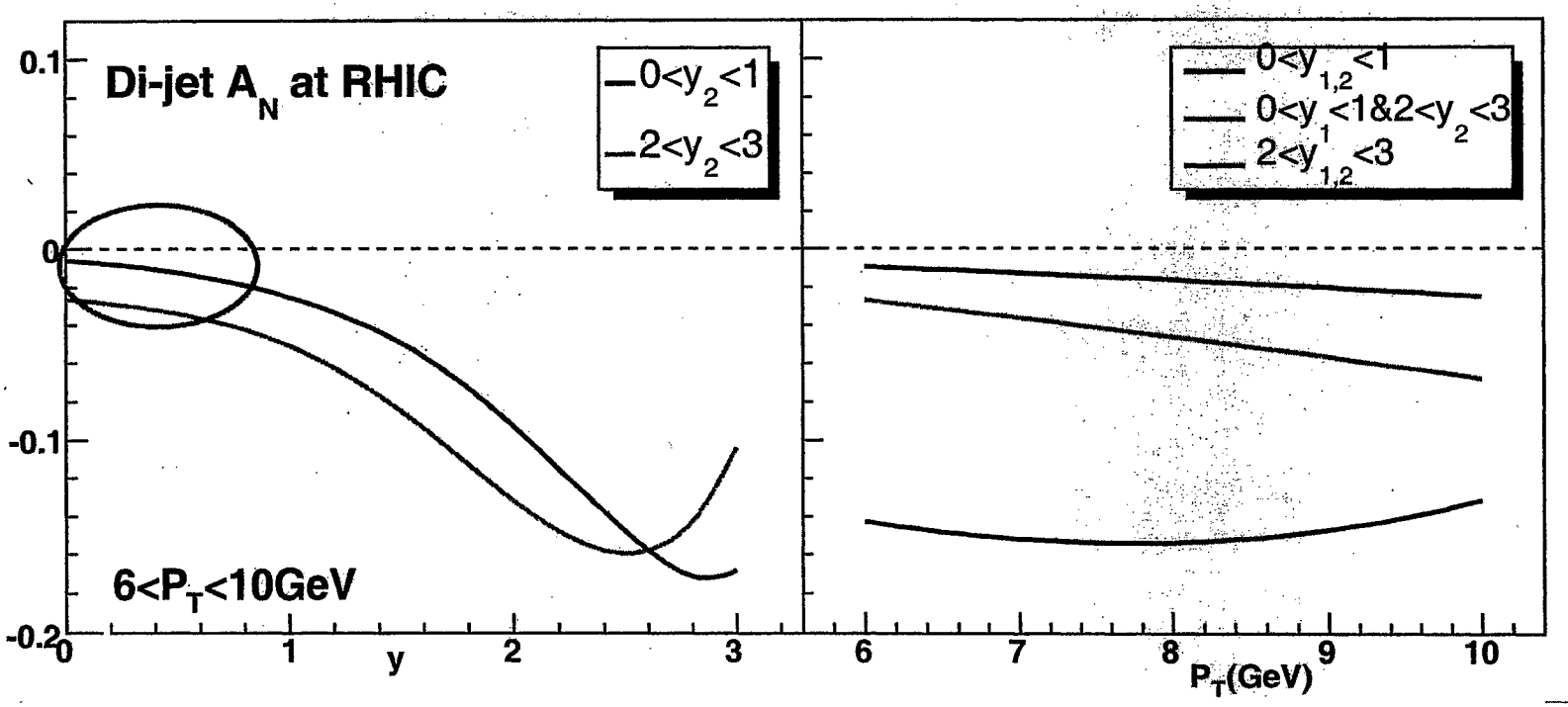
Di-jet Correlation



$$\vec{S}_\perp \times \hat{\vec{q}}_\perp \approx |S_\perp| \left(\mathrm{Sgn}(\pi - \theta) \cos\phi_1 + \sin\phi_1 \frac{|q_\perp|}{2|P_\perp|} \right)$$

$$\begin{aligned} d\sigma &\propto d\sigma_{UU} + \vec{S}_\perp \times \hat{\vec{q}}_\perp d\sigma_{TU} \\ &= d\sigma_{UU} + \cos\phi_1 d\sigma_{TU}^{(1)} + \sin\phi_1 d\sigma_{TU}^{(2)} \end{aligned}$$

cosϕ Asymmetry



Thermalization in the Color Glass Condensates

Kirill Tuchin

Thermalization in the Color Glass Condensate

Kirill Tuchin

Iowa State University and RBRC

In collaboration with D. Kharzeev and E. Levin

Modern picture of AA collisions

- Initial state: the Color Glass Condensate
  - Particle spectra, multiplicities …
- Final state: the Quark Gluon Plasma
  - Elliptic flow, jet quenching …

What is the mechanism which evolves CGC into QGP?

The main puzzle at RHIC

Hydrodynamic models are successful if thermalization time ~t≈0.5fm.

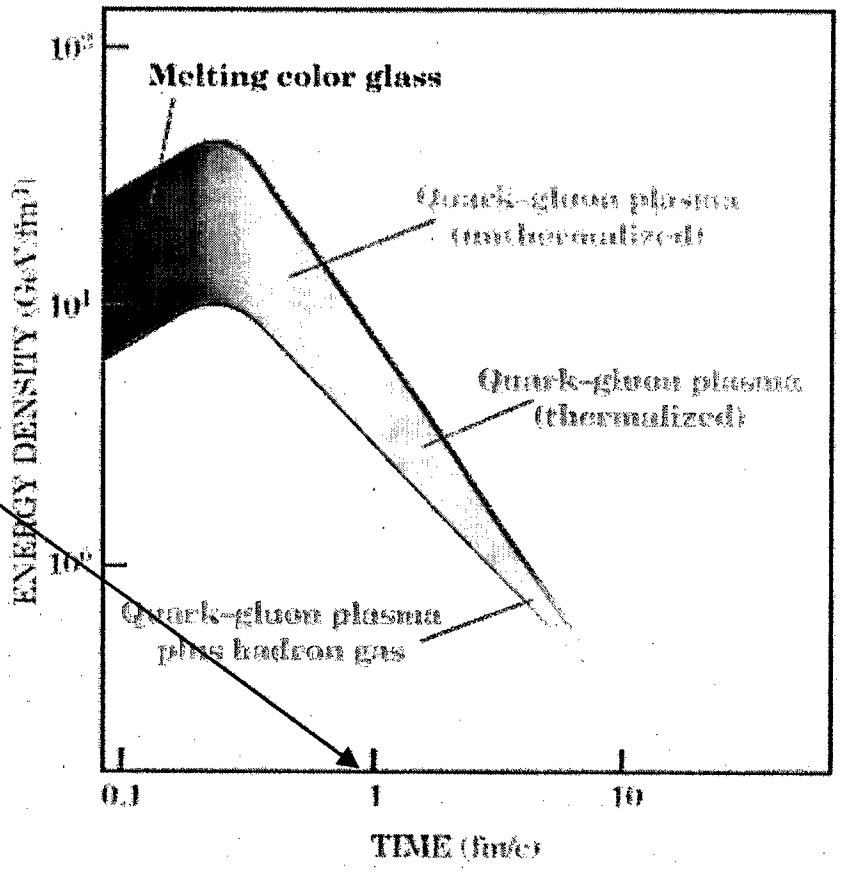
Naively:
~t~1/(n~)~1 fm/~$_s$>>1 fm

Why thermaization is so fast??

- "Bottom-up thermalization":

$$\alpha t = 1/\alpha_s^{13/5} Q_s$$

Baier, Mueller, Schiff, Son, 01



Possible solutions?

- Plasma instabilities may speed up the thermalization process

Mrowczynski, 88;
Arnold,Lenaghan, Moore,03

✓However, ~t is still very close to "bottom-up" estimate.

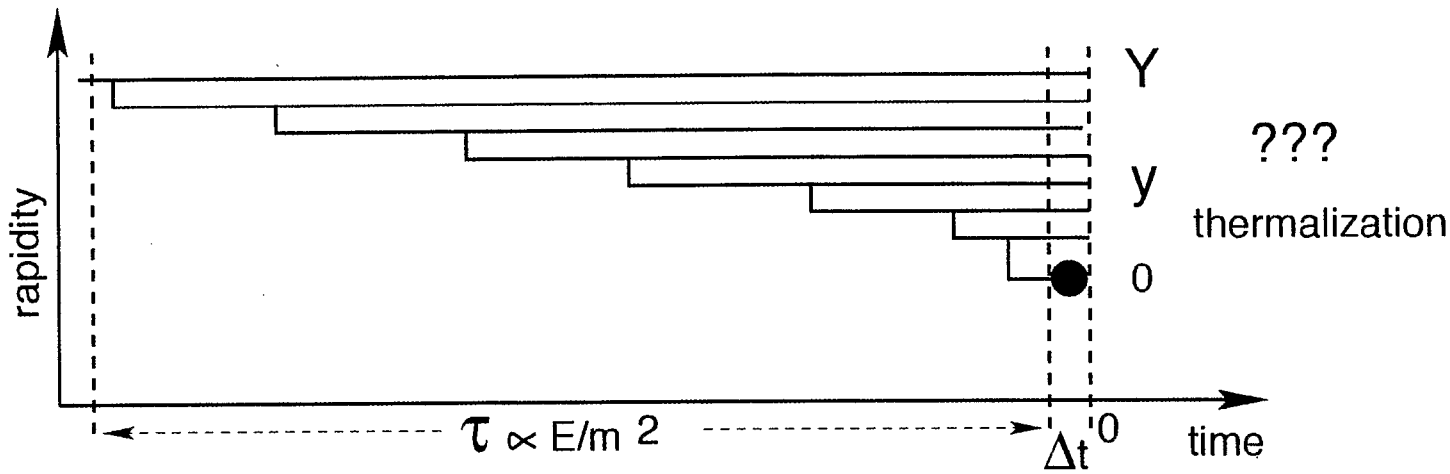
- Early isotropization may help explain v_2.

Arnold,Lenaghan,Moore,Yaffe,04;
Rebhan,Romatschke,Strickland,04

- No thermalization from Feynman diagrams.

Kovchegov, 05

Basic CGC



1. Parton lifetime is $\Delta_i = k_i^+ / k_{i\Delta}^{\ 2} >> \Delta_{i+1} >> \Delta t$ (Parton model)
2. Fast partons are sources of the classical field.
   (McLerran, Venugopalan)

Properties of dense partonic system

1. 2D density $Q_s^2 \sim xG(x,Q_s)/\lambda R_A^2 \sim 1/x^\lambda$
   is a hard scale increasing with rapidity $y = \ln(1/x)$

- Typical transverse size of a parton $x_\perp \sim 1/Q_s$ decreases down the partonic ladder.
- The potential $A_+(x_\approx \approx x_{i\approx}, x_\approx \approx x_{i\approx}) \approx A_+(x_\approx, R_\approx)$
- Therefore, $|E_\perp| = |H_\perp| << E_z$
- Even at small x_- longitudinal electric field dominates the Lagrangian.

Early and later times

2. Since evolution of fast partons is frozen in time, the color field E_z of faster partons is constant at t=0.

3. At later times the lightcone potential of the pointlike charge is $A_+ \sim 1/x_-$.

- We calculate particle production in an external time-dependent background field.

- This calculation makes it possible to include nonperturbative effects.

- Model potential: $$A_+(x_-) = -E_0 \frac{x_-}{x_-^2 \omega^2 + 1}$$

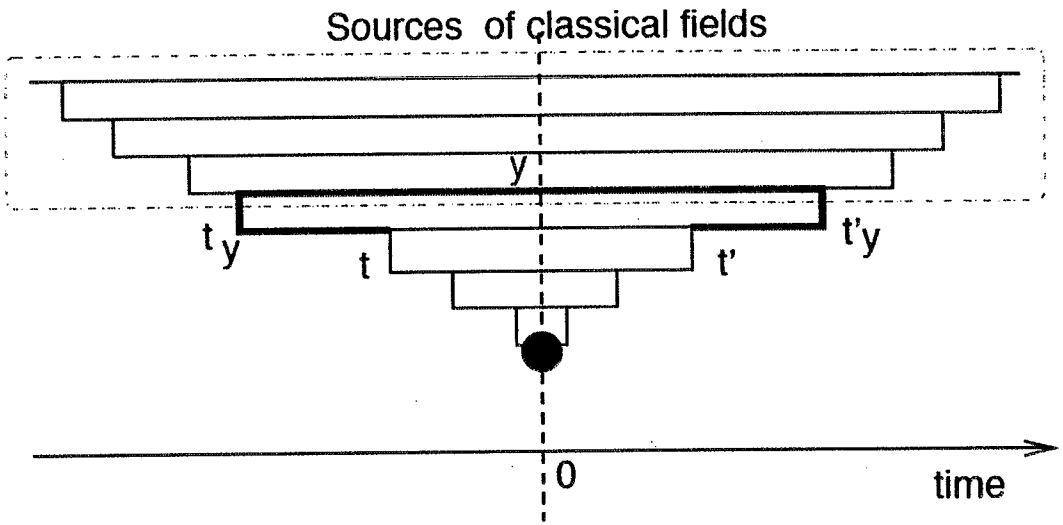
Our formalism

- Inclusive gluon production cross section is

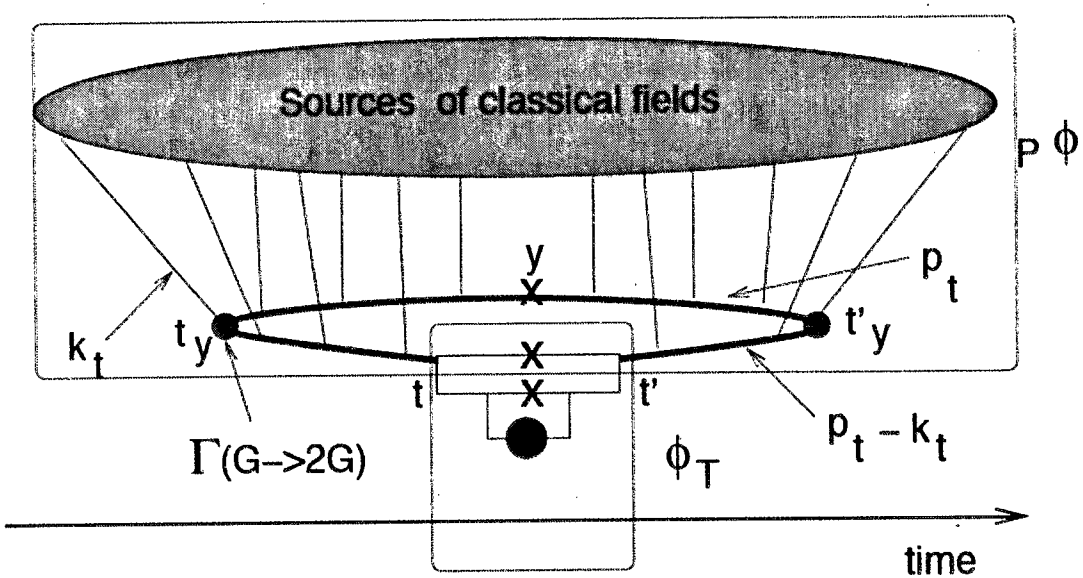
$$\varepsilon \frac{d\sigma}{d^3p} = \frac{4\pi N_c}{N_c^2 - 1} \frac{1}{p_\perp^2} \int dk_\perp^2 \; \alpha_S \, \varphi_P(Y - y, k_\perp^2) \, \varphi_T(y, (p-k)_\perp^2)$$

- Unintegrated gluon distribution is related to the imaginary part of the gluon propagator:

$$\varphi_P(Y - y, p_\perp) = \int d^2 k_\perp \Gamma^2(G \to 2G) \, \mathrm{Im} D(Y - y, \vec{p}_\perp - \vec{k}_\perp) \, \mathrm{Im} D(Y - y, \vec{p}_\perp)$$


Sources of classical fields
y
t_y
t
t'
t'_y
0
time

=


Sources of classical fields
$P\ \phi$
y
p_t
k_t
t_y
t'_y
t
t'
Γ(G->2G)
ϕ_T
$p_t - k_t$
time

Solution

Equation of motion of the quantum field W_μ

$$\left(-(\partial_\lambda - igA_\lambda)^2\,\delta_{\mu\nu} + 2i\,g\,F_{\mu\nu}[A]\right)\,W_\mu = 0$$

Can be solved in the WKB approximation for the function $S = i \ln W$

Known solutions:

- ✓ exact in Minkowski spacetime in constant field: Sauter (1931), Weisskopf (1936), Schwinger (1951);
- ✓ WKB in Minkowski spacetime in any field: Popov (1972);
- ✓ in WKB in Schwarzschild metric: Hawking (1973).

Lightcone coordinates

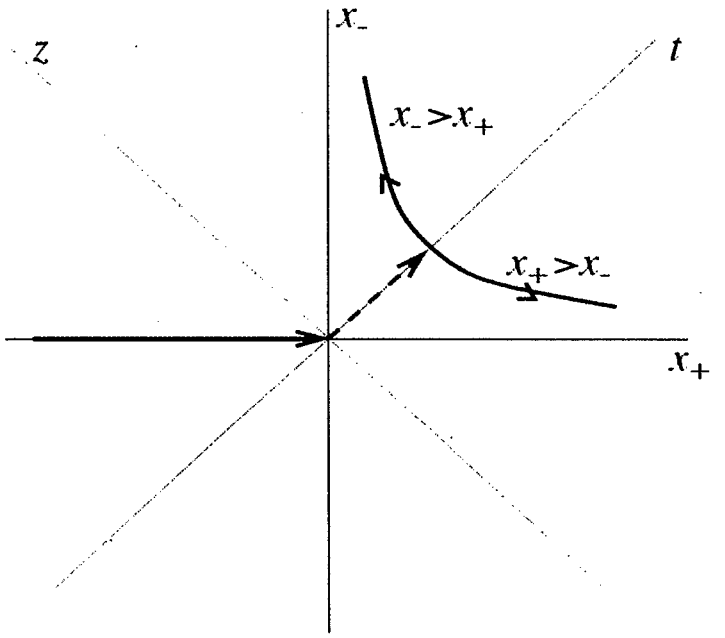


FIG. 3: Motion of a particle in the light-cone coordinates. We used (26b) and (26c) to derive parametric equation $x_+ x_- = p_\perp^2 t^2$ (assuming $x_+^0 = x_-^0 = 0$). At $x_+ < 0$ the particle moves freely along the light cone $x_- = 0$ until the point $x_- = x_+ = 0$ at which it tunnels along the line $x_- = x_+$ (Euclidean path, shown by dashed line) to a real trajectory at $x_+ > 0$. At this point particles move along $x_+ > x_-$ branch of the parabola, while antiparticles along the $x_+ < x_-$ branch.

Adiabaticity parameter

$$\omega = \frac{k_\omega \omega}{gE_0}$$

- Early times: $\approx\approx \frac{k_+}{k_{i+}} << 1$

$$-_P(p_-) \sim S_P e^{-p_-{}^2/Q_s{}^2}$$ This is MV model !

- Later times: due to interactions between the gluons the frequency ~~k_- increases from 0 to Q_s γ $\gamma \sim 1$

$$\varepsilon_P(p_\varepsilon) \sim S_P e^{\varepsilon\varepsilon/T}$$

Where T=0.17 Q_s. Equallibration time follows from equation of motion: ~~$1/Q_s$

Summary

- We develop an approach to the particle production at high energy which incorporates the main idea of the CGC as well as the non-perturbative Schwinger-type mechanism.
- Within this approach we
  - reproduce the McLerran-Venugopalan result at early times of the collision, when the fields are static;
  - show that the particle spectrum is thermal at later times, when the fields rapidly oscillate;
  - argue that the transition time between the two regimes is short.
- Our approach is applicable also to DIS.

Quarkonia Correlators Above Deconfinement

Ágnes Mócsy

Quarkonia Correlators Above Deconfinement

Áanes Mócsy

RIKEN BNL Research Center

RBRC Scientific Review Committee Meeting, BNL October 10, 2005

* Why interested in quarkonia correlators
* How to calculate correlators
* Phenomenology versus lattice
* Open questions

based on A.M., P. Petreczky : hep-ph/0411262
hep-ph/05

Why interested in quarkonia correlators ?

Tell about the modification of quarkonia properties in a hot medium.

Efforts to identify deconfinement - experiments SPS-CERN, RHIC-BNL...
- theory, phenomenology
- lattice QCD

* Screening prevents J/ψ binding above T_c Matsui,Satz '86

color screening length < size of resonance

* Sequential dissolution - higher excitations melt earlier Digal, Petreczky, Satz '01

Potential Model J/ψ disappears at $1.1T_c$

$T = 0$ — Cornell potential

$T \neq 0$ We don't know. e.g. screened Cornell potential

Ágnes Mócsy

Lattice QCD

* J/ψ melts abruptly at $1.6T_c < T < 1.9T_c$ Umeda; Asakawa, Hatsuda '04

* J/ψ, η_c survive ~ $1.5T_c$ & gradually melt by ~ $3T_c$ + masses don't change

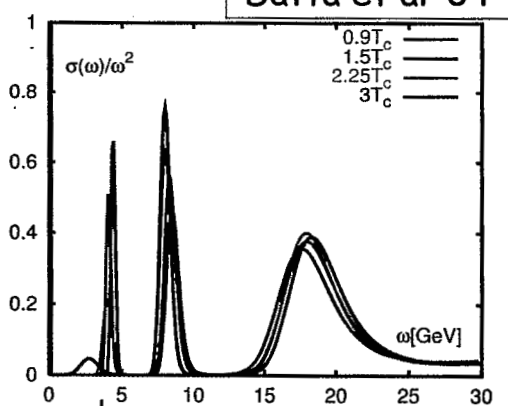
  χ_c^0, χ_c^1 dissolve ~ $1.1T_c$ Datta, Karsch, Petreczky, Wetzorke '04

* η_b unchanged ~ $2T_c$ & χ_b at ~ $1.15\ T_c$ Petrov, Petreczky QM05

Euclidean current correlator measured

Spectral function – w/ MEM

Datta et al '04



J/ψ artifacts ignored

Can quarkonia exist as resonances above deconfinement ?

How to calculate correlators

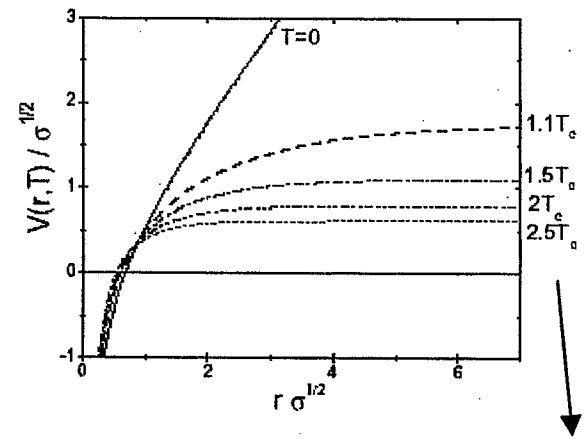
* Model spectral function: bound states + continuum

* Mass M_i, amplitude F_i, radius R_i from Schrodinger equation w/

screened Cornell potential
OR
potential fitted to lattice internal energy

* Threshold $s_0(T) = 2\, m_q(T) = 2m + V_1(T)$

* Correlator ratio:
deviation from 1 suggests medium effects

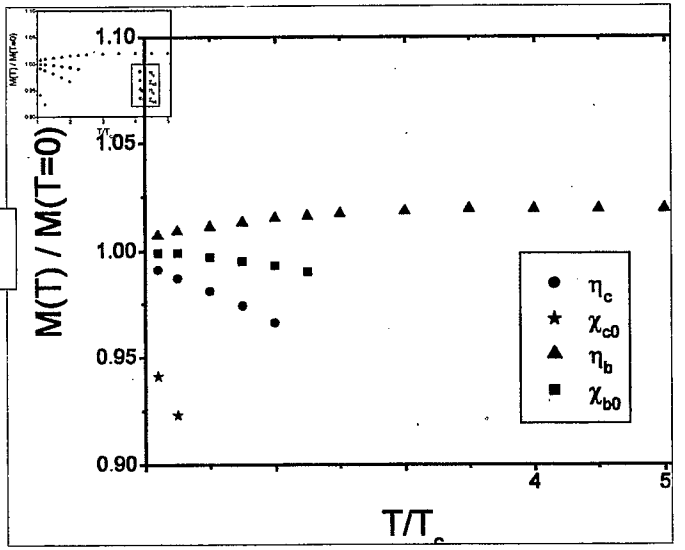


asymptotic value $V_1(T)$

Ágnes Mócsy

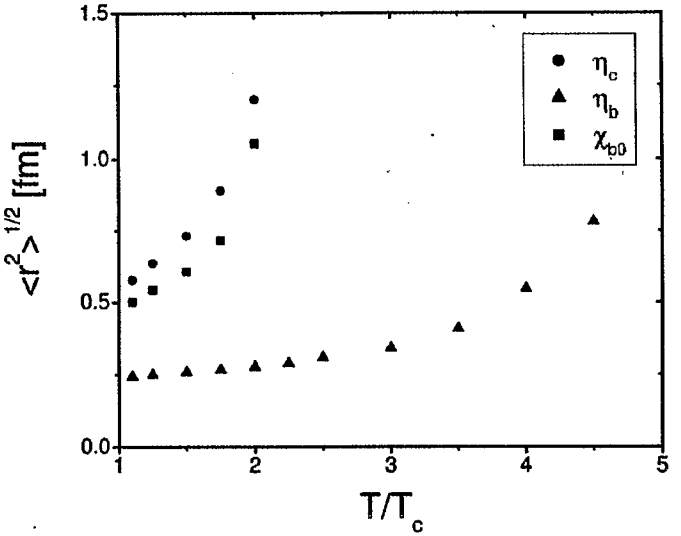
Quarkonia properties

Masses



don't change substantially, except the χ_c

Radii



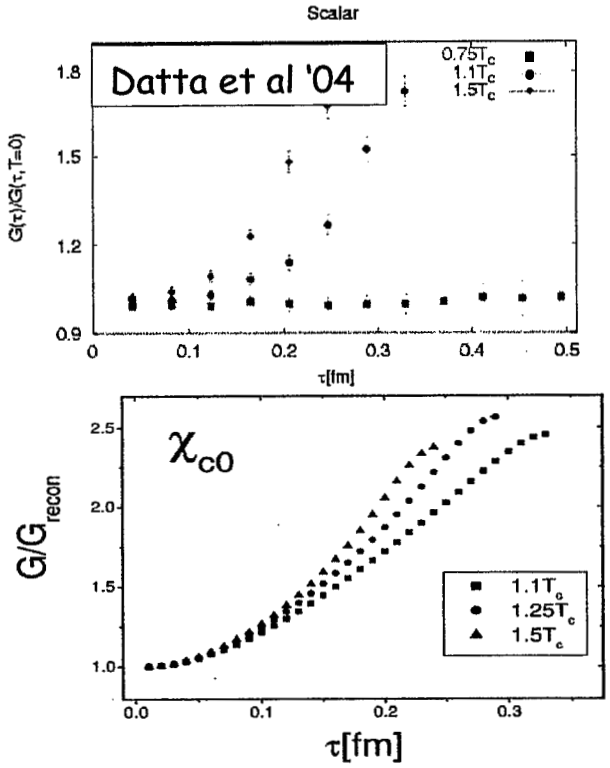
χ_{co} melts early

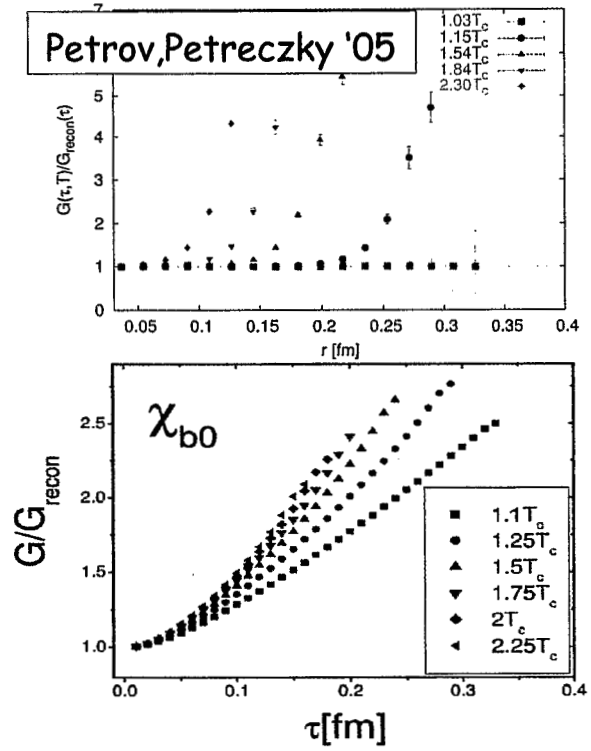
$b\bar{b}$ survive to higher T than $c\bar{c}$

χ_b approximately same size as η_c

Ágnes Mócsy

Phenomenology vs. Lattice : 1P Scalar





χ_{c0} modified at ~$1.1T_c$

χ_{b0} modified at ~ $1.13\ T_c$

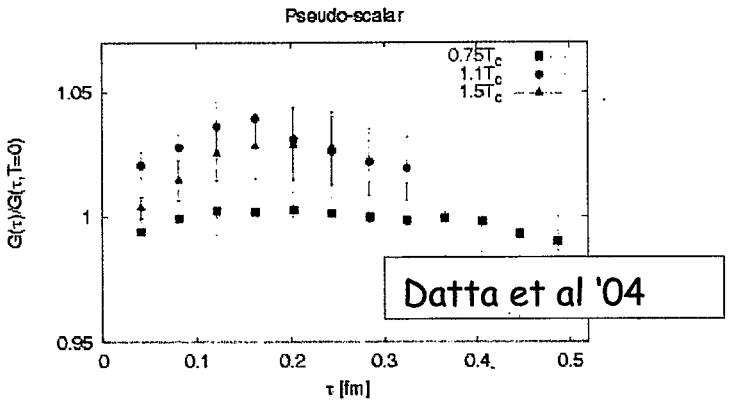
Qualitative agreement w/ lattice.

Correlator enhanced, even though χ_{c0} state becomes negligible

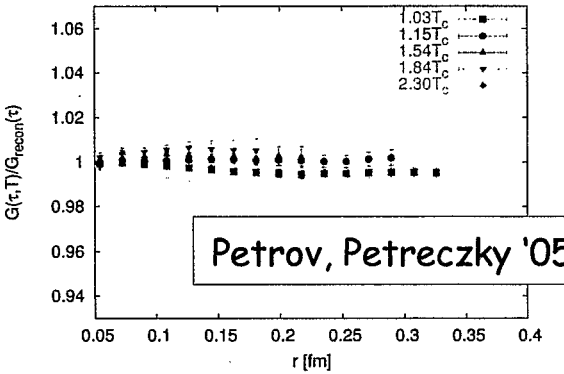
Qualitatively ~ behavior, even though χ_b survives until much higher T than χ_c

Enhancement due to thermal shift of the continuum threshold - domintes

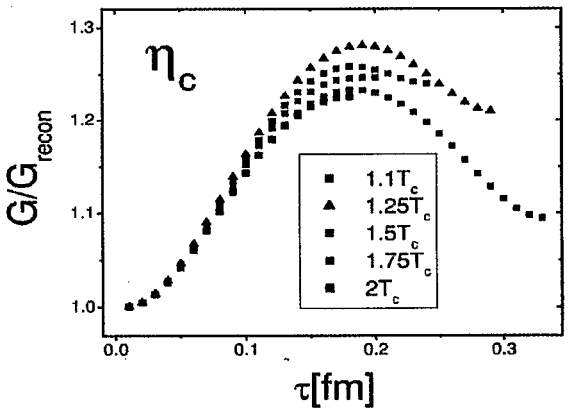
Phenomenology vs. Lattice : 1S Pseudoscalar

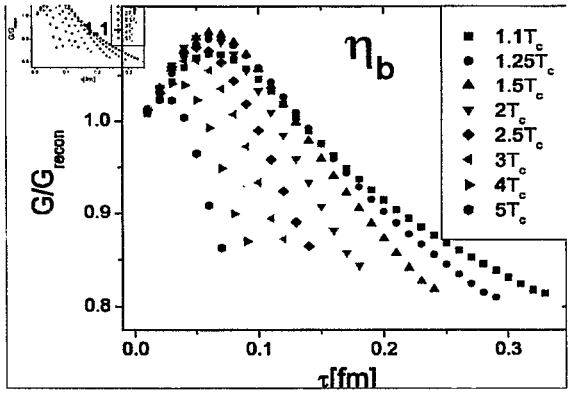


Datta et al '04



Petrov, Petreczky '05





Increase in correlators

No agreement w/ lattice.

Contribution from continuum due to threshold reduction

Drop at large τ in η_b due to amplitude reduction

Ágnes Mócsy

Conclusions & Open Questions

Quarkonia melting at T_c - proposed sign for deconfinement challenged by lattice data - some quarkonia survives well above T_c

First analysis of quarkonia correlators in potential model

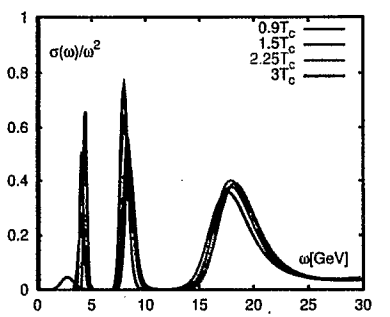
T-dependence of the correlators not in agreement with the lattice

Increase in correlators - due to threshold decrease -- lattice doesn't see

Tested w/ different potentials -
no qualitative changes in the T-dependence of the correlators

* Can medium effects on heavy quark boundstates be described by potential models?

* Do we miss some physics on the lattice?
Info about continuum hidden in the lattice artifacts ?



Ágnes Mócsy

Properties of the Plasma Created at RHIC

Denes Molnar

Properties of the plasma created at RHIC

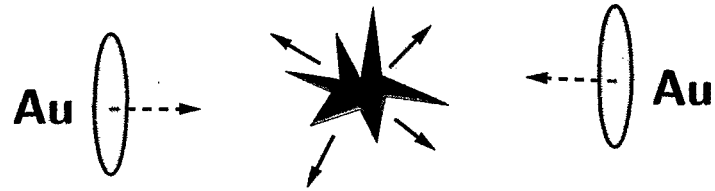
Denes Molnar

Aug 15, 2005 - RIKEN/BNL Research Center & Purdue University
previously - Ohio State University

prepared for RBRC Review

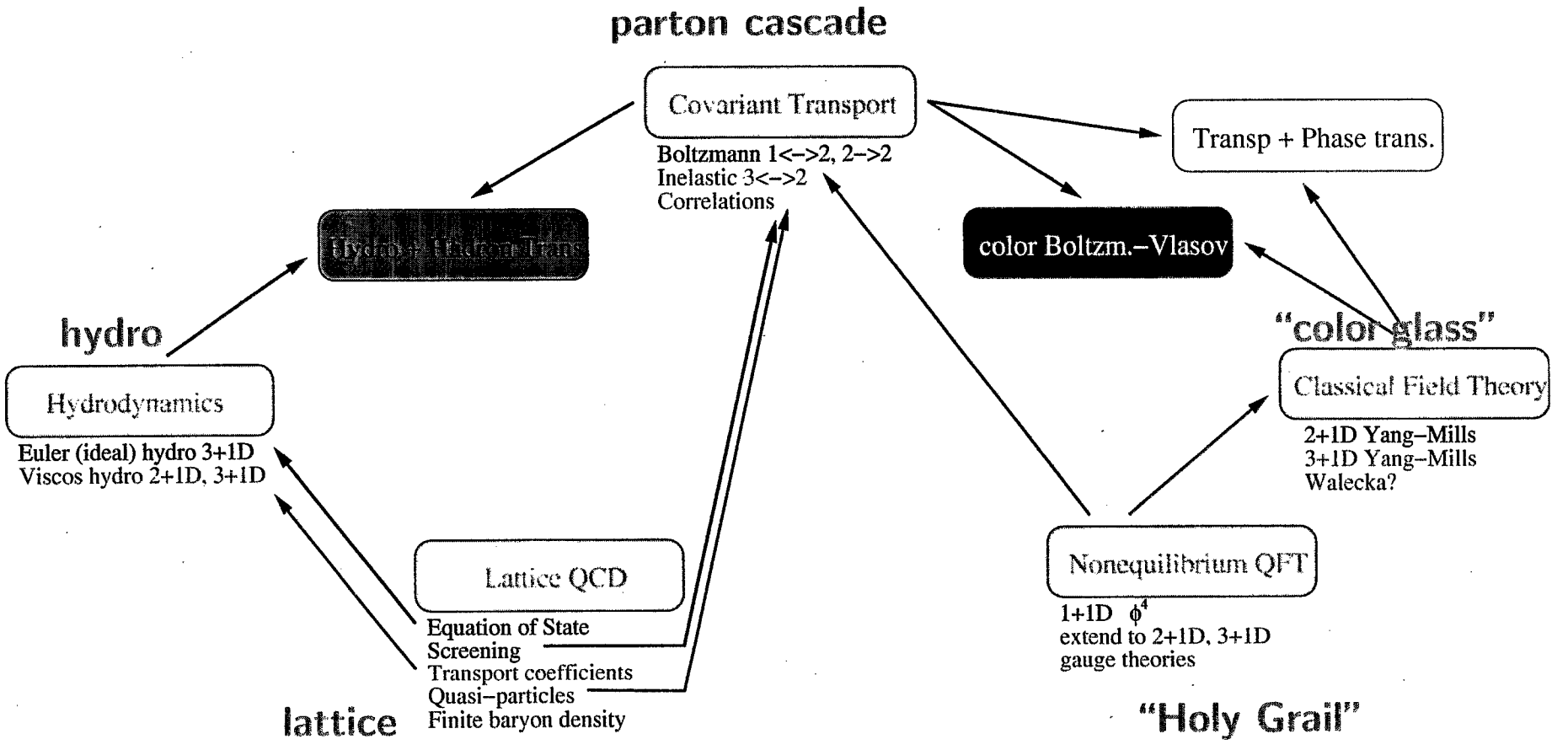
Oct 10-12, 2005, RIKEN/BNL, Upton, NY

RHIC "Little Bang"



quark-gluon plasma?

Dynamical frameworks



Quark-gluon kinetic theory

Pang, Zhang, Gyulassy, DM, Vance, Csizmadia, Pratt, Cheng, ...

Incoherent, particle limit of underlying quantum theory (QCD) . **Nonequilibrium approach.**

Boltzmann transport eqn: $f_i(\vec{x},\vec{p},t)$ - quark/gluon phase space distributions

$$p^\mu \partial_\mu f_i(\vec{x},\vec{p},t) = \overbrace{S_i(\vec{x},\vec{p},t)}^{\text{source}} + \overbrace{C_i^{el.}[f](\vec{x},\vec{p},t)}^{2\to 2\ (\mathrm{ZPC,GCP,...})} + \overbrace{C_i^{inel.}[f](\vec{x},\vec{p},t)}^{2\leftrightarrow 3\ (\mathrm{MPC,Xu-Greiner})} + \ldots$$

- **on-shell dynamics** $(p^2 = m^2 \geq 0)$

other variants: e.g., VNI(b), off-shell partons Kinder-Geiger, Shrivastava, Mueller, Bass, ...

*** OSCAR code repository @ http://nt3.phys.columbia.edu/OSCAR ***

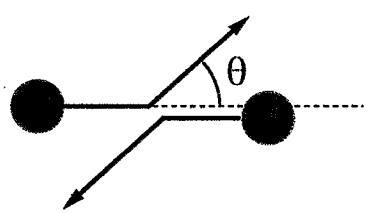
Relevant parameters

mean free path: characterizes local conditions

$$\lambda(x) \equiv \frac{1}{\text{cross section} \times \text{density(x)}} \qquad \begin{cases} \lambda = 0 & - \text{ideal hydrodynamics} \\ \lambda = \infty & - \text{free streaming} \end{cases}$$

transport opacity: time-integrated, spatially averaged [DM & Gyulassy NPA 697 ('02)]

$$\chi \equiv \langle n_{coll} \rangle \langle \sin^2 \theta_{CM} \rangle \quad \sim \# \text{ of collisions per parton} \times \text{mom. transfer efficiency}$$

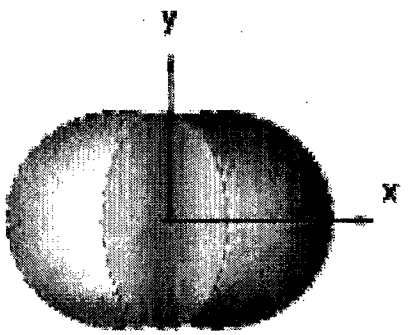


Elliptic flow (v_2)

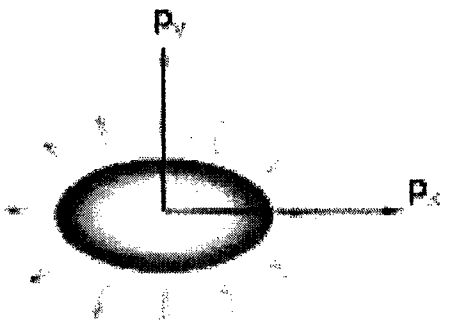
one of the most important observables

spatial anisotropy $\longrightarrow$ final azimuthal momentum anisotropy

$$\varepsilon \equiv \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$



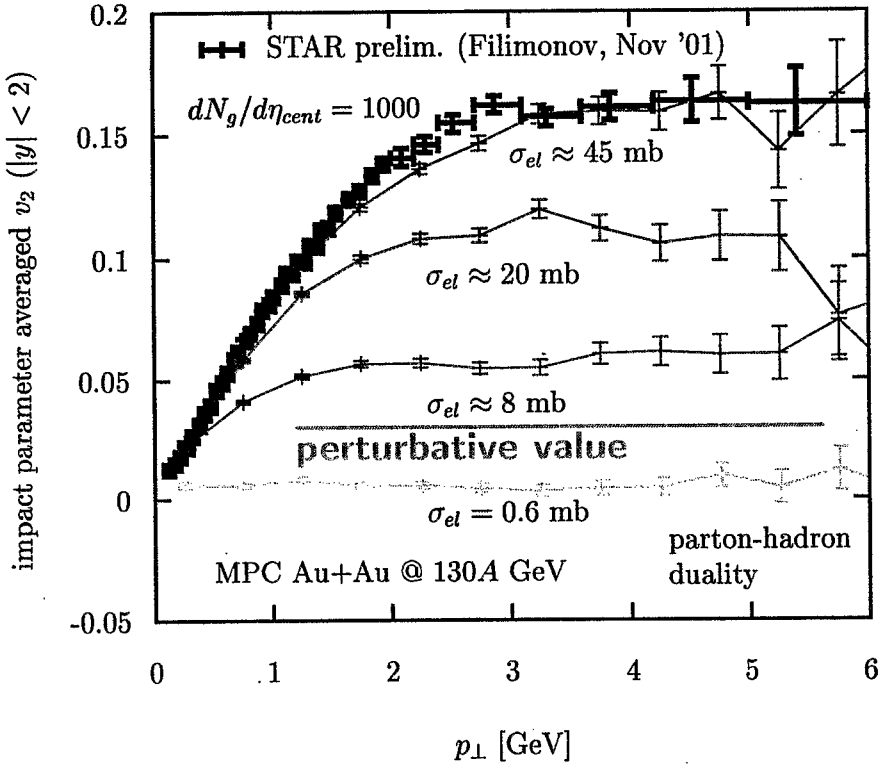
$$\longrightarrow \quad v_2 \equiv \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$



- measures strength of interactions
- **self-quenching, develops at early times**

Strong interactions at RHIC

DM & Gyulassy, NPA 697 ('02): $v_2(p_T, opacity)$



Au+Au @ 130 GeV, $b = 8$ fm

nonlinear opacity dependence

$$v_2^{max} \sim \chi^{0.61} \sim (\sigma \times dN/dy)^{0.61}$$

need $15\times$ **perturbative opacities** - $\sigma_{el} \times dN_g/d\eta \approx 45$ **mb** $\times 1000$

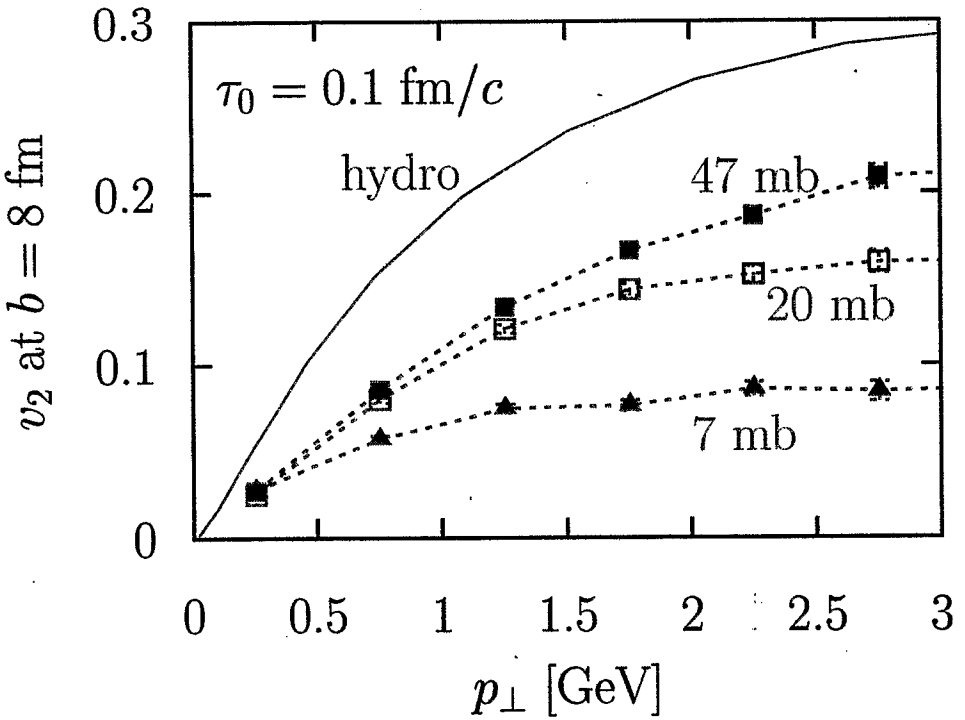
(saturated gluon $\frac{dN^{cent}}{d\eta} = 1000$, $T_{eff} \approx 0.7$ GeV, $\tau_0 = 0.1$ fm, 1 parton $\rightarrow$ 1 π hadronization)

$\Rightarrow$ **strongly-interacting quark-gluon plasma (sQGP)**

Still not ideal fluid(!)

Even $\sigma_{gg\to gg} \sim 50$ mb is insufficient for ideal hydro (perturbative QGP: ~ 3 mb)

DM & Huovinen, PRL94 ('05):



- **dissipation reduces v_2 by $30 - 50\%$**
- **in addition, it slows cooling**

was already seen in 1+1D transport

Gyulassy, Pang & Zhang ('97)

also there in 1+1D viscous hydro

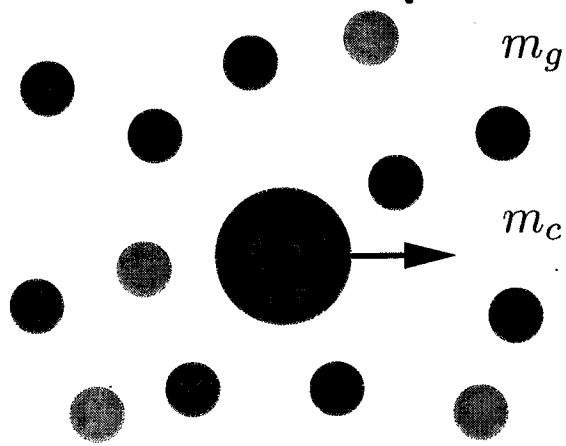
Danielewicz & Gyulassy ('85)

$$\frac{d\epsilon}{d\tau} + \frac{\epsilon + p}{\tau} = \frac{(\zeta + \frac{4}{3}\eta)}{\tau^2}$$

viscosity very small - but gradients very large

Heavy quark equilibration

$\sim$ **"Brownian motion" in plasma**



$m_g, m_{u,d}, m_s \sim T$

$m_c \sim 1.2$ **GeV** $\gg T$

$v \sim \sqrt{T/m}$

$p \sim \sqrt{m \cdot T}$

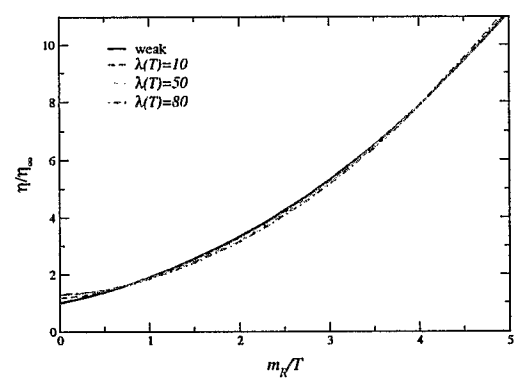
$N_{coll} \sim p/\Delta q \sim \sqrt{m/T}$

heavy quarks very heavy $\Rightarrow$ need more collisions to randomize

more quantitative indicator: viscosity grows with mass

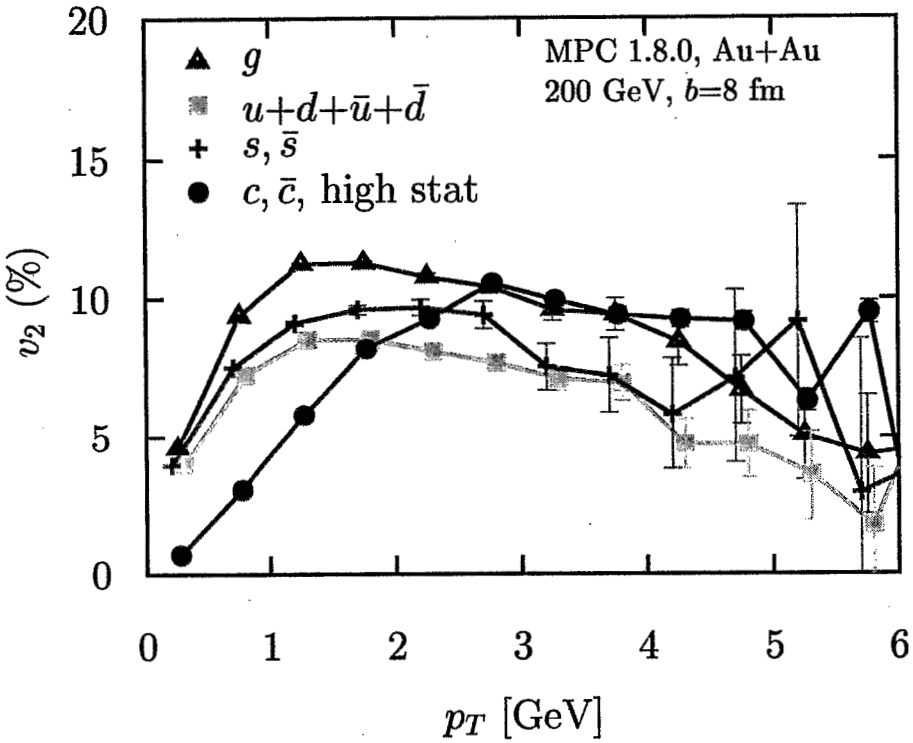
classical kinetic theory: $\eta \approx 0.553\sqrt{mT}/\sigma_{el}$

$O(N)$ **model:** Aarts & Martinez ('04) $\longrightarrow$

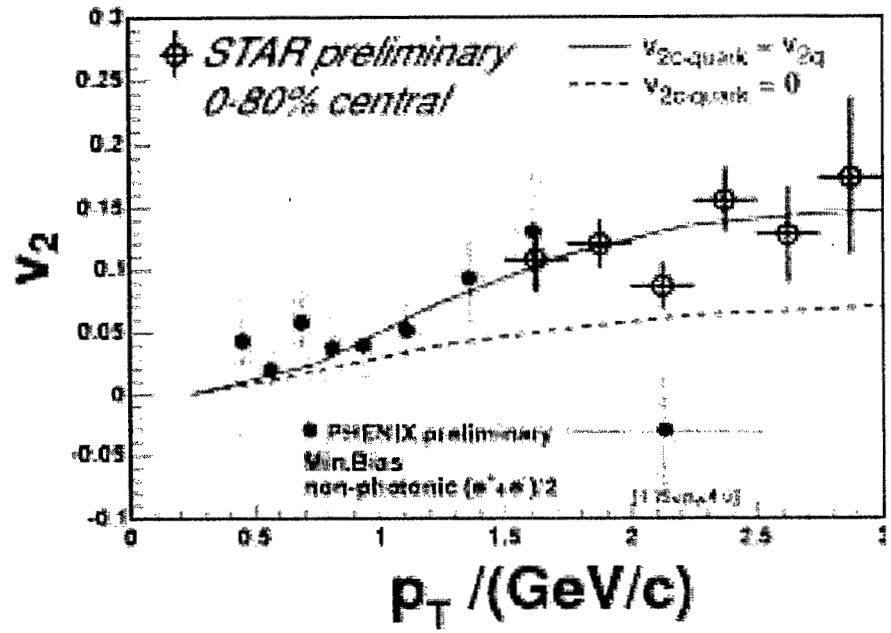


Expect charm elliptic flow

DM, JPG 31 ('04): **parton** $v_2(p_T)$



Laue [STAR] '04: **decay electron** $D \to K^{(*)}\, e\, \nu$ **data**



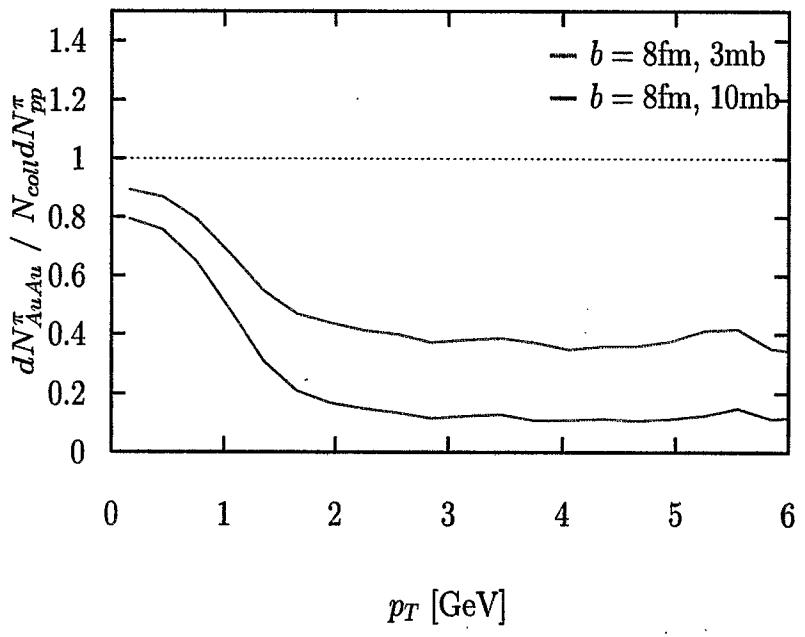
significant charm equilibration in opaque plasma,
charm v_2 **reaches light parton** v_2 **above** $p_T > 2-3$ **GeV**

similar results from parton cascade ZPC Zhang et al '05, **Fokker-Planck approach** Teaney et al '05

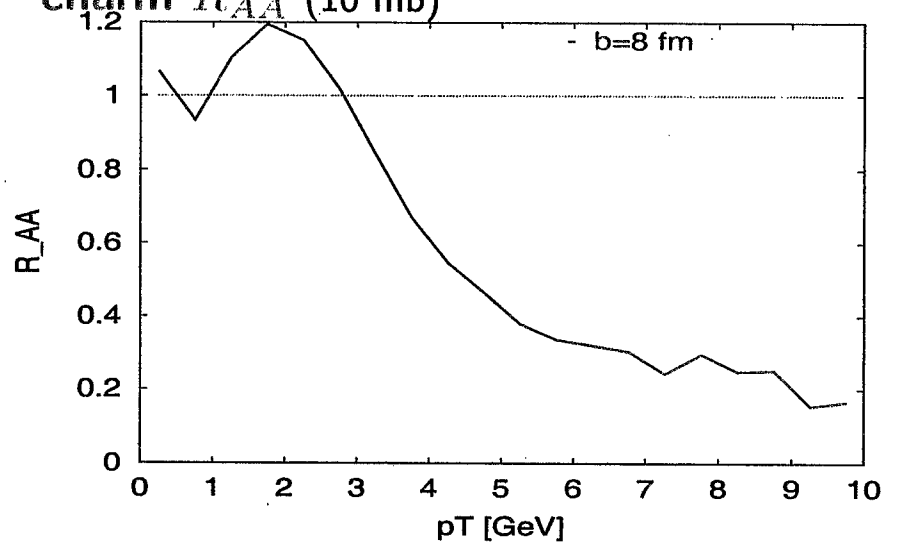
Charm suppression at high-pT

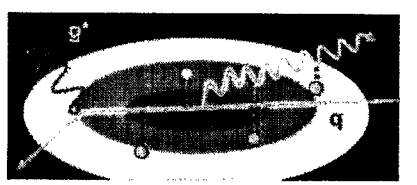
$$R_{AA} \equiv \frac{yield\ in\ A+A\ collision}{yield\ for\ independent\ N+N\ scatterings}$$

DM '04: **pion** R_{AA}



charm R_{AA} (10 mb)





canonical explanation: suppression is due to energy loss

expect weaker suppression for charm than for light hadrons at high pT

current excitement/puzzle: data suggest similar suppression for light and charm(?!)

Plasma "push" DM '05

in opaque plasma, initially soft partons can get accelerated to surprisingly high p_T in multiple collisions

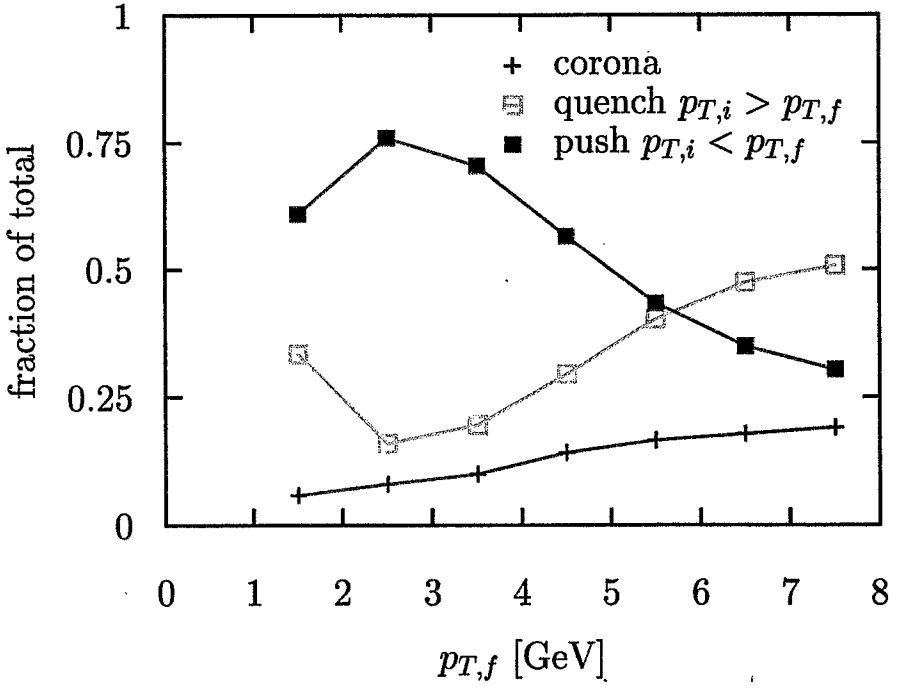
⇒ **three components:**

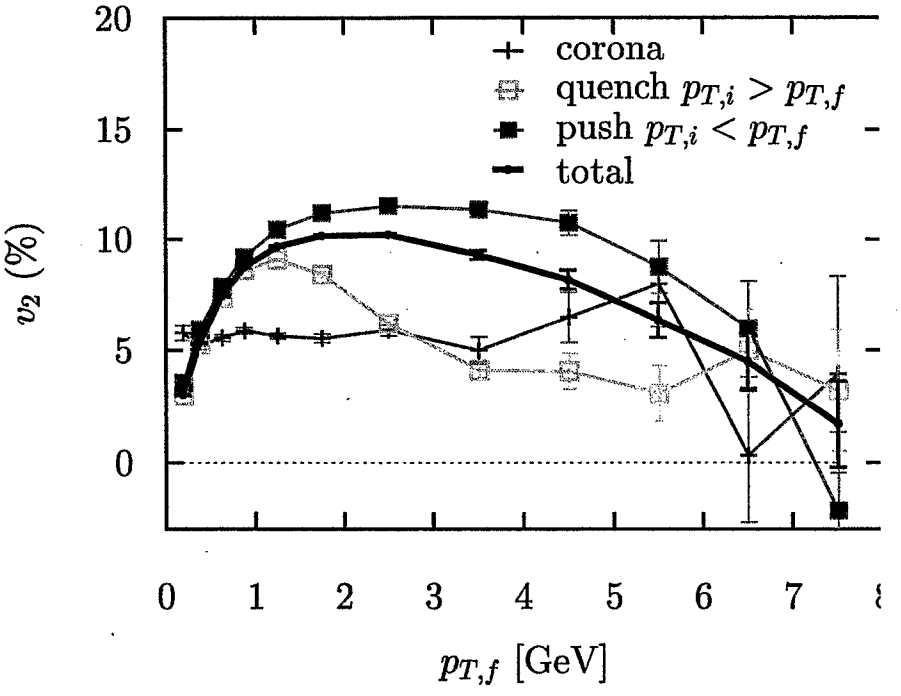
- energy loss → partons that lose energy via interactions
- **corona → partons that escape without interactions**
- **"push" → partons that interact and gain energy**
  ("remnant" of hydrodynamic behavior)

corona, quench, push fractions vs pT

elliptic flow contributions vs pT

DM, nucl-th/0503051: $\sim 6\times$ pQCD opacities





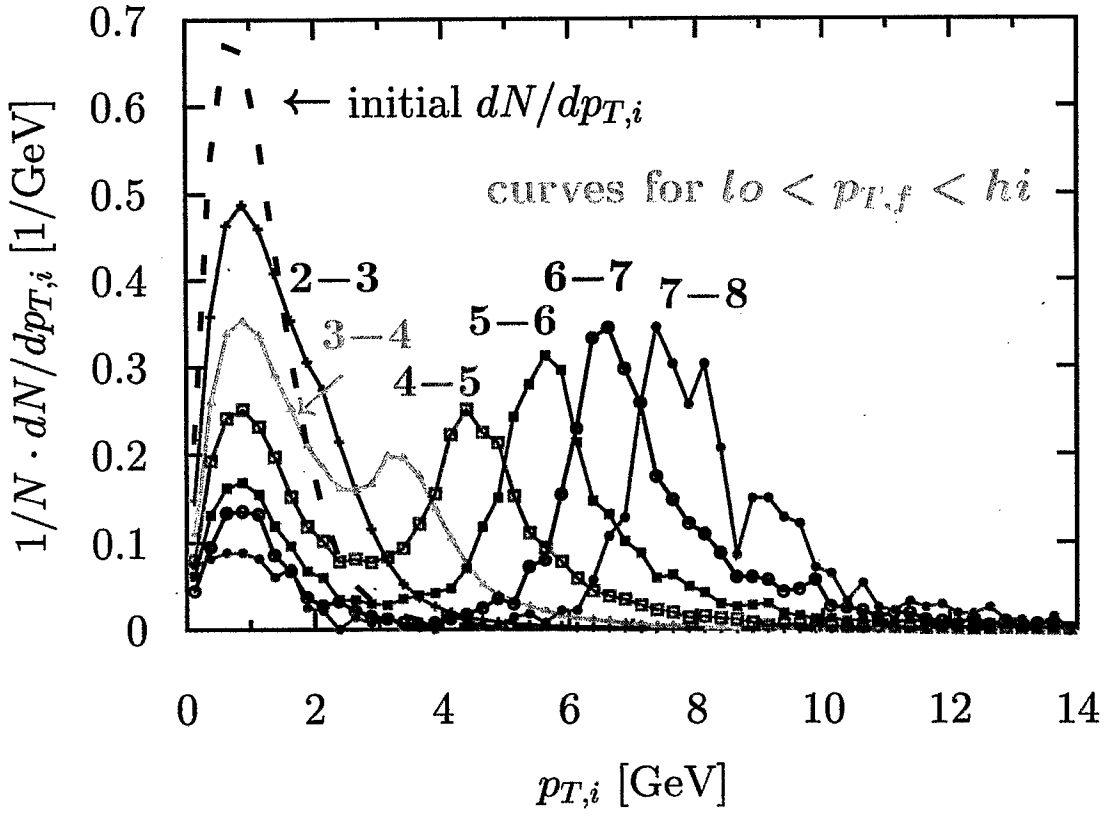
significant $\sim 20\%$ "push" component even at $p_T \sim 8$ GeV

v_2 is higher and decreases slower at high p_T relative to pure energy loss case

distribution of initial momenta for fixed final momentum bins, $|y_{fin}| < 1$

(only quench + "push" plotted, normalized)

DM, nucl-th/0503051: $\sim 6\times$ pQCD opacities



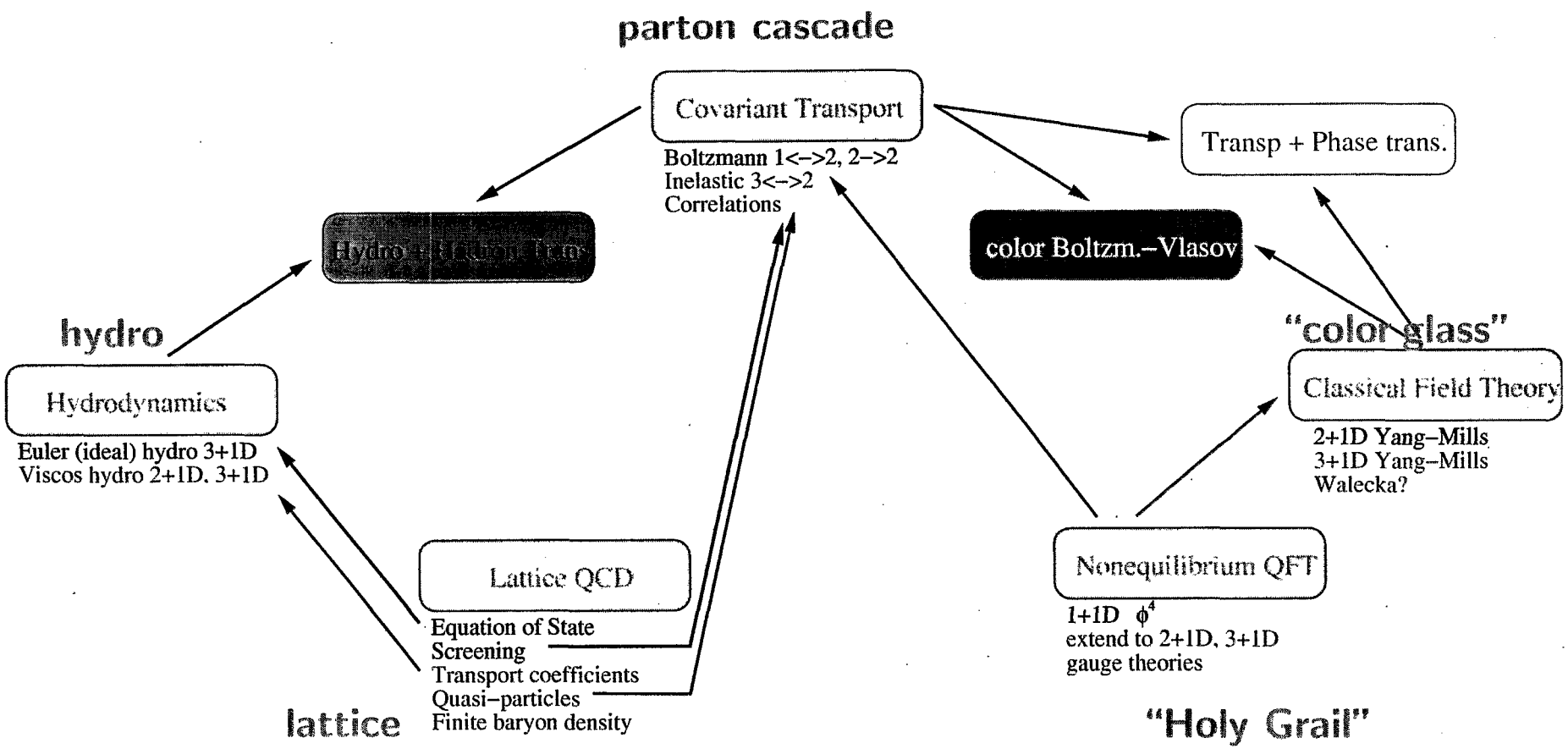
"lucky" $p_{T,i} \sim 1$ GeV soft partons can end up at $p_T \sim 7-8$ GeV

Conclusions

- What we learned:
  - large elliptic flow observed at RHIC indicates a very opaque parton system
  - but even 45 mb elastic parton-parton cross sections are insufficient to reach the ideal hydrodynamic limit $\Rightarrow$ not ideal fluid
  - at such extreme opacities significant charm quark elliptic flow is expected at moderately high $pT > 2 - 3$ GeV
  - also, initially soft partons can get accelerated to surprisingly high p_T in multiple collisions $\Rightarrow$ energy loss is not the only mechanism that plays a role

- Open issues/Next steps:
  - map out parameter space - centrality, A, collision energy (LHC), bottom, ...
  - improve parton cascade - inelastic channels, coherence effects
  - compare to simpler limits - viscous hydrodynamics (Navier-Stokes), Fokker-Planck
  - combine with classical fields - QCD analog of plasma physics

Need to build bridges



establish an international collaboration for QCD transport theory

Charge Transfer Fluctuations as a QSP Signal

Sangyong Jeon

Charge Transfer Fluctuations as a QGP signal

Sangyong Jeon
with Lijun Shi & Marcus Bleicher

Physics, McGill

RBRC

Charge Transfer Fluctuations

(Thomas, Quigg, Chao (1973), Shi, Jeon, hep-ph/0503085, To appera in PRC)

- Charge Transfer:

$$u(y) = [Q_F(y) - Q_B(y)]/2$$

where

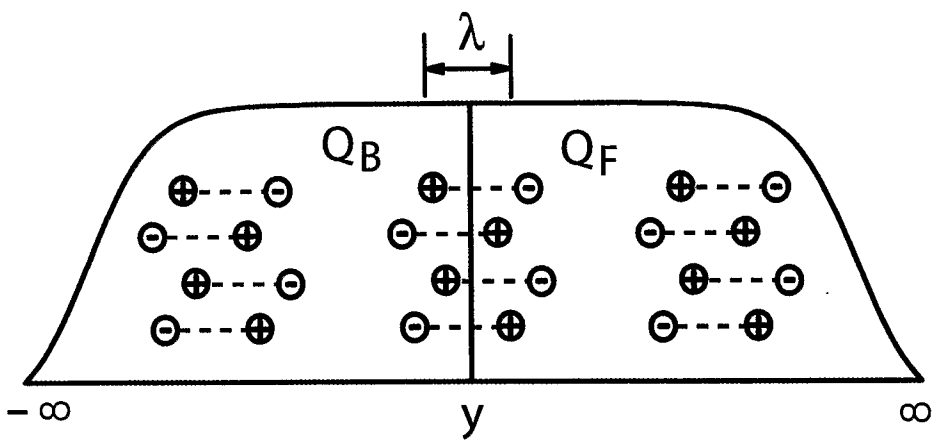
$$\begin{cases} Q_F(y) = \text{Net charge in the forward region of } y \\ Q_B(y) = \text{Net charge in the backward region of } y \end{cases}$$

Observable: $$\boxed{\kappa(y) \equiv \frac{\langle \Delta u(y)^2 \rangle}{dN_{\text{ch}}/dy}}$$

- Suppose a neutral cluster R decays near y.
  - $R \longrightarrow h^+ + h^-$ with a typical $\Delta y = \lambda$
  - For each R decay, $u(y)$ changes by $\pm 1 \Longrightarrow$ <u>Random walk</u>
  - $D_u(y) = \langle \Delta u(y)^2 \rangle = N_{\text{steps}}(y) \approx \lambda \dfrac{dN_{\text{cluster}}}{dy}$
  - Since $dN_{\text{cluster}}/dy \propto dN_{\text{ch}}/dy$,

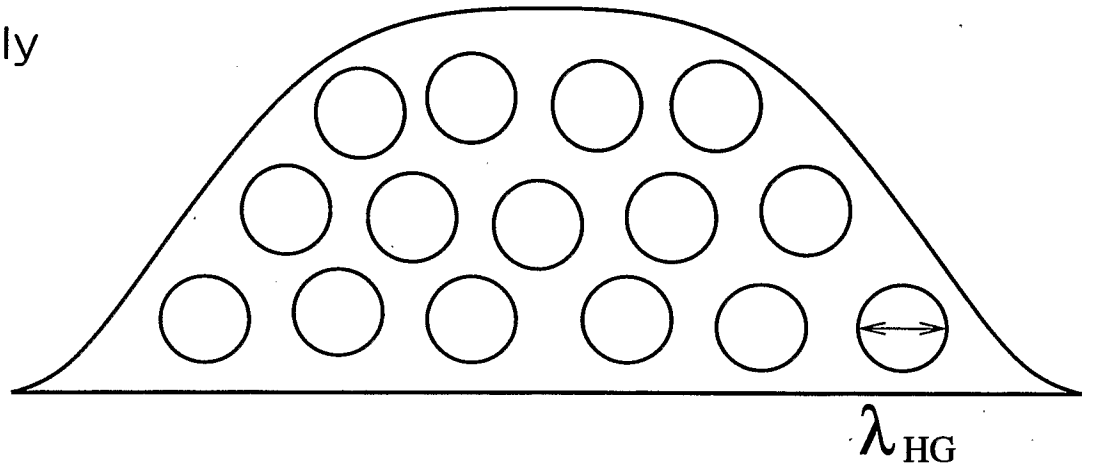
$$\boxed{\kappa(y) \equiv \frac{D_u(y)}{dN_{\text{ch}}/dy} \propto \lambda(y)}$$

Measures the *local* charge correlation length.

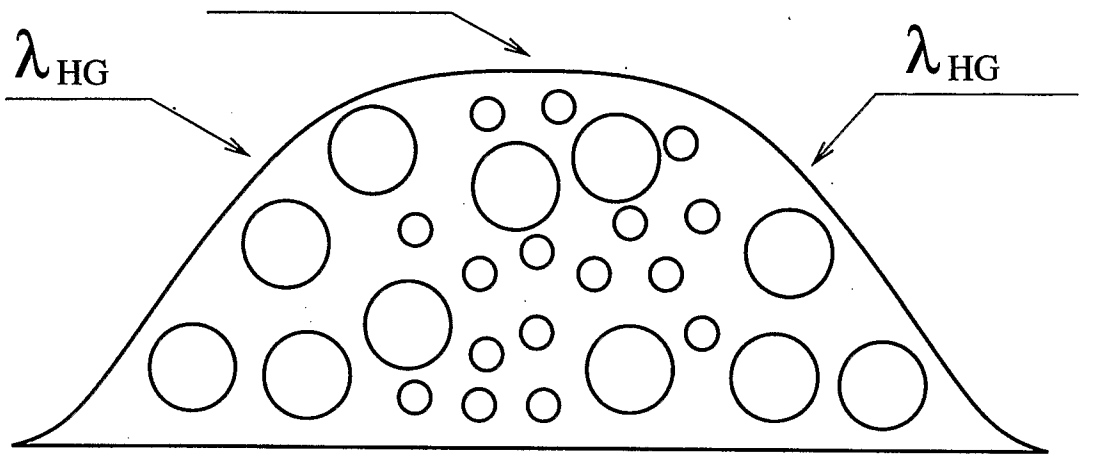


The difference:

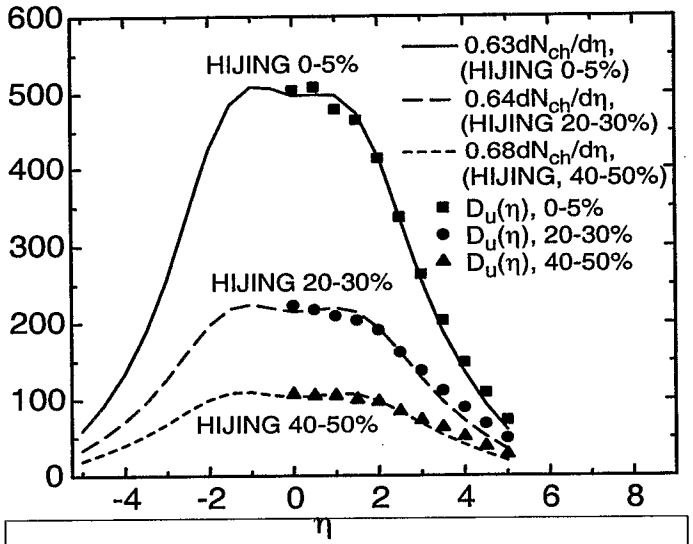
Hadron Gas only

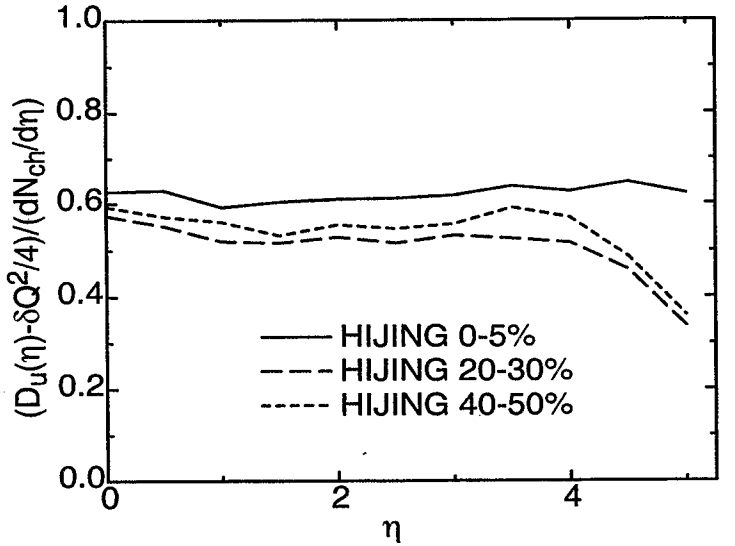


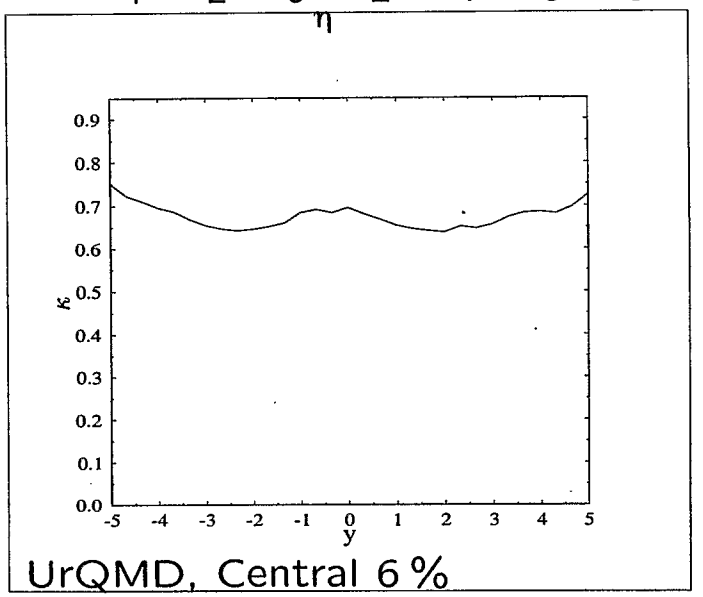
Hadron Gas + QGP $p\lambda_{QGP} + q\lambda_{HG} < \lambda_{HG}$

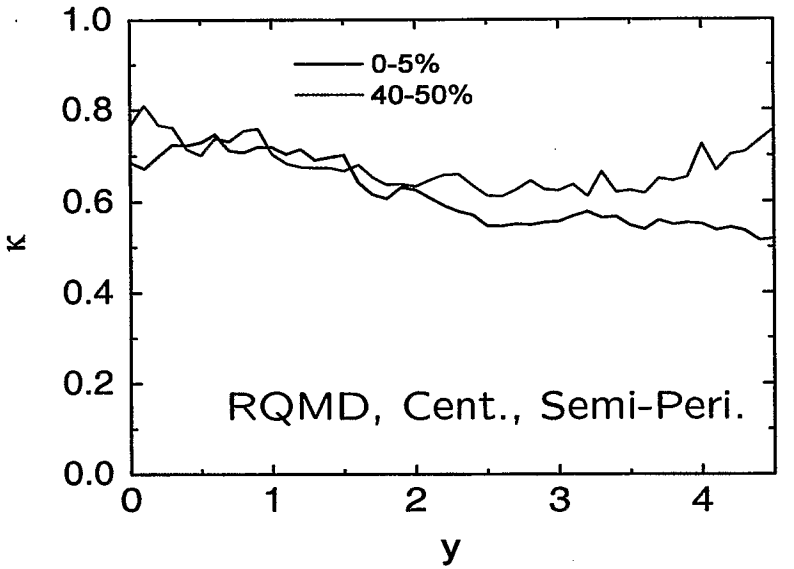


Hadronic models $\Longrightarrow$ constant κ

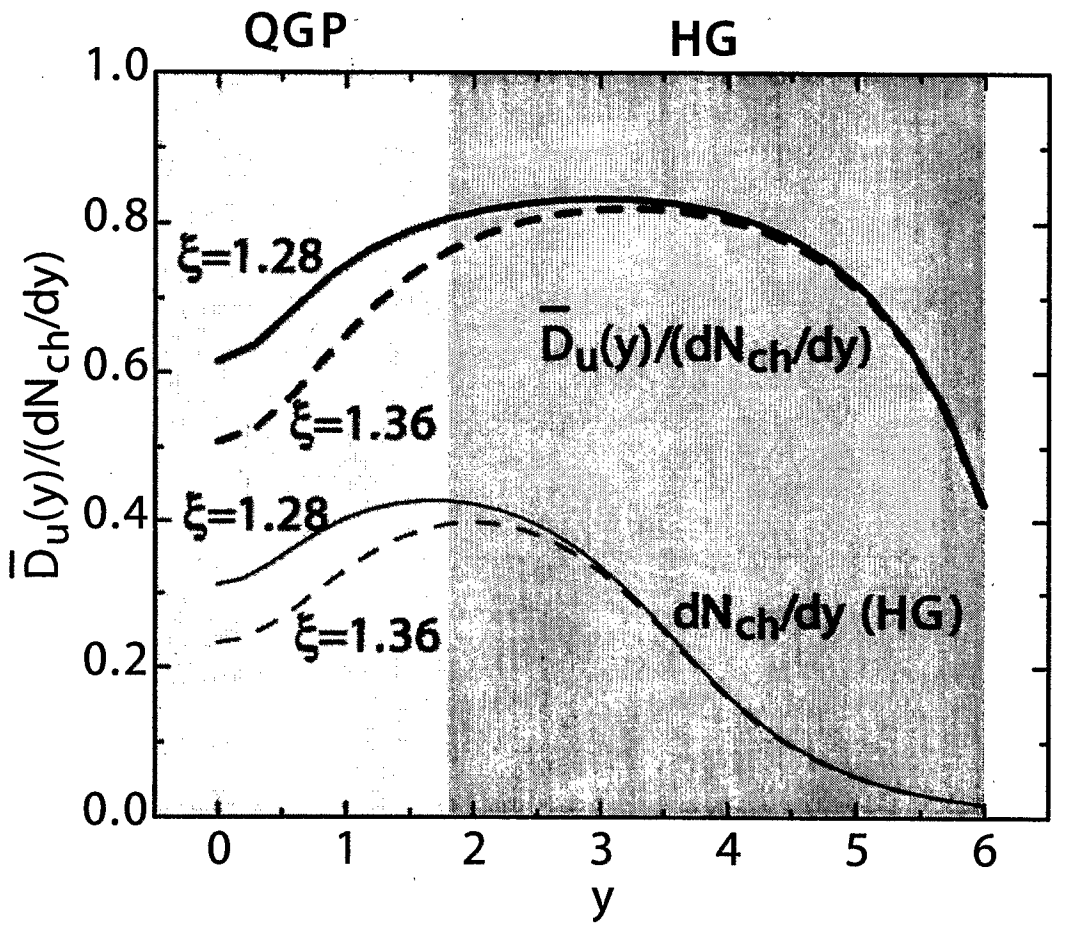








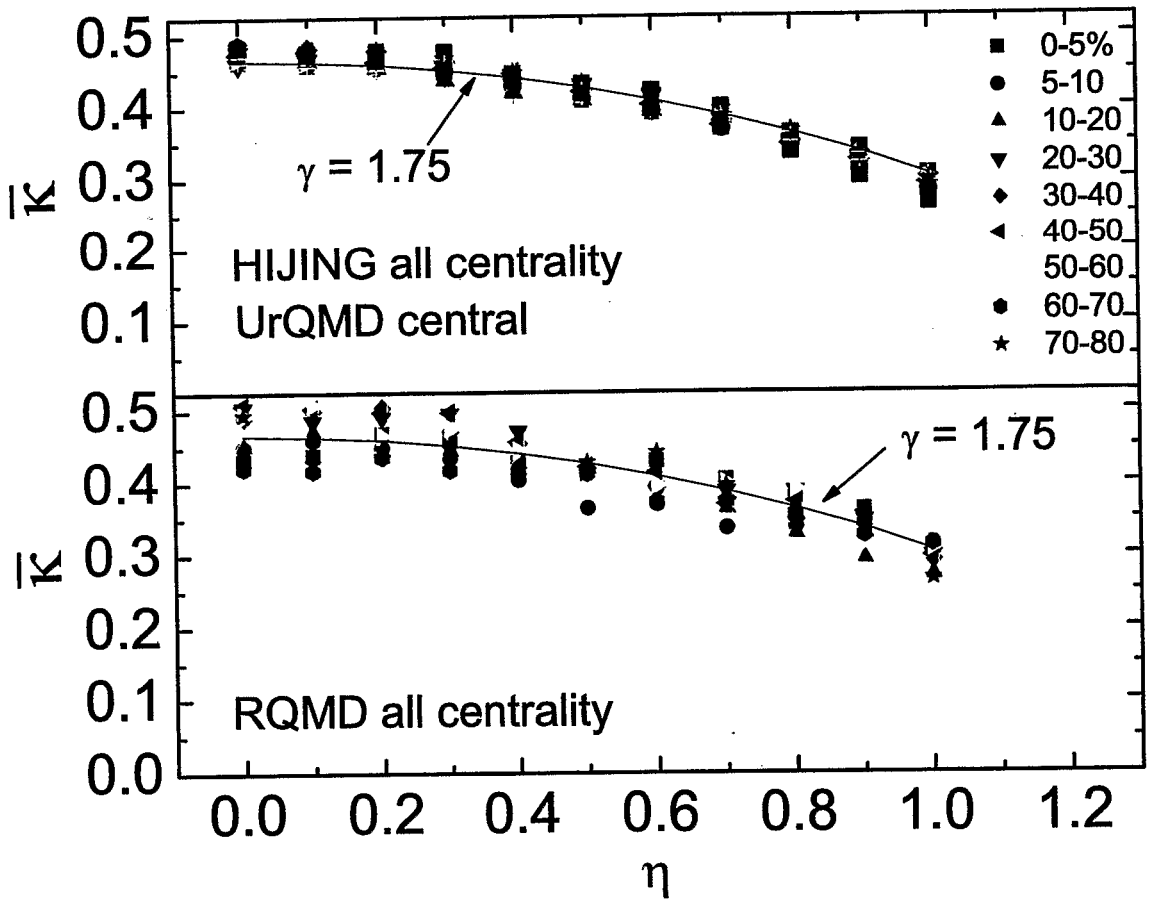
HG + QGP – Full η space



$$\kappa(\eta) = \frac{\gamma_{\rm HG}}{2} - \frac{\gamma_{\rm QGP}}{2}\left(\frac{\gamma_{\rm HG}}{\gamma_{\rm QGP}} - 1\right)\frac{dN_{\rm QGP}/d\eta}{dN_{\rm ch}/d\eta}$$

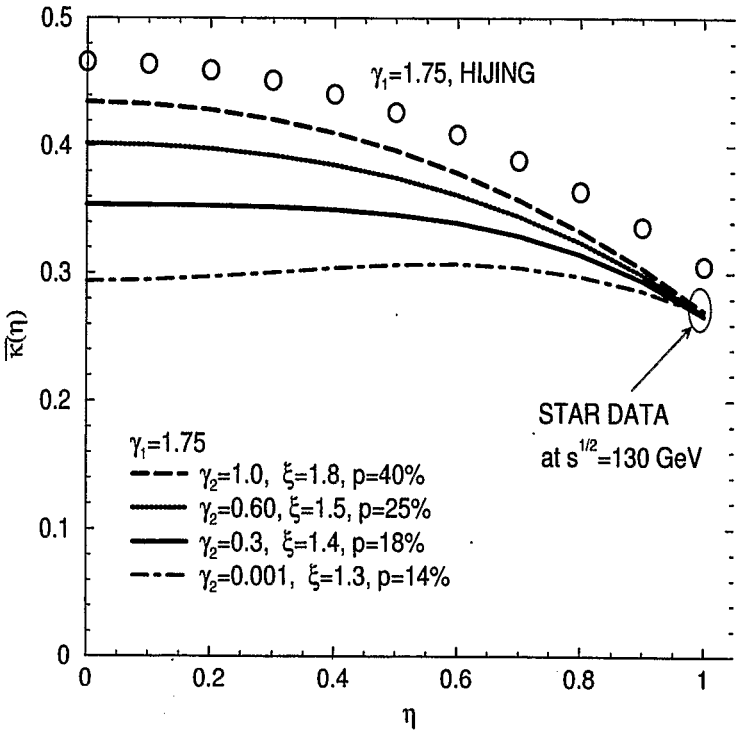
HG – STAR acceptance

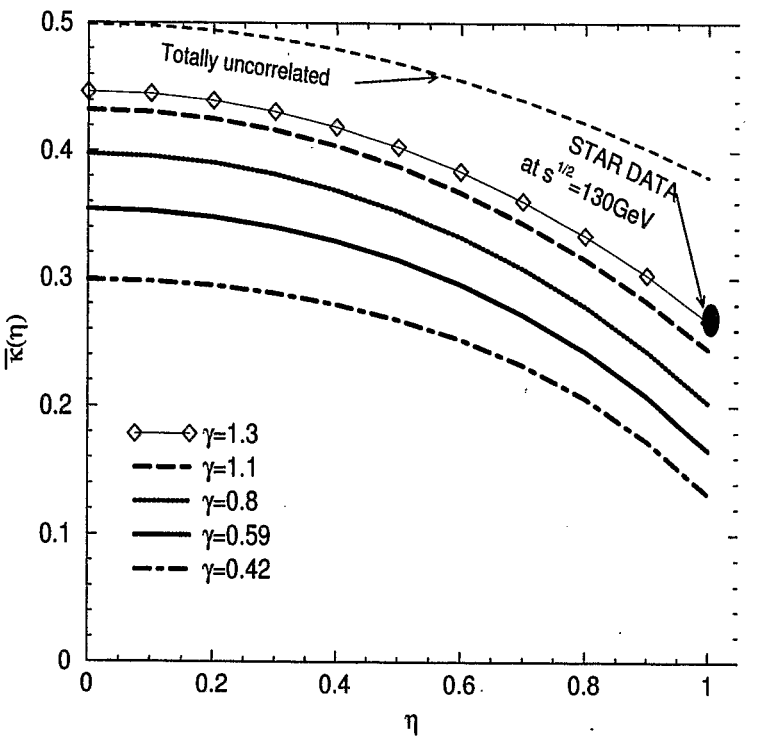
Hadronic models with the single component results



HG + QGP – STAR acceptance

End point fixed by $\langle \Delta Q^2 \rangle / N_{\mathrm{ch}}$





Conclusions

- Charge transfer: $u(y) = (Q_F(y) - Q_B(y))/2$
- $\kappa(y) \equiv \langle \Delta u(y)^2 \rangle / dN_{\text{ch}}/dy$: A measure of *local* charge correlation length $\Longrightarrow$ Captures *inhomogeneity*
- QGP may be created in a small region around midrapidity. As collisions become more central
  - Large acceptance: $\kappa(y)$ develops a dip in the middle
  - Small acceptance: $\kappa(0)$ becomes smaller faster than $\kappa(y_o)$ $\Longrightarrow$ Flattening
- Net baryon transfer fluctuation. Net strange transfer fluctuation
- $\langle \Delta N^F_{\text{ch}}(y) \Delta N^B_{\text{ch}}(y) \rangle$

Effective Action for High Energy QCD with the Pomeron Loop

Yoshitaka Hatta

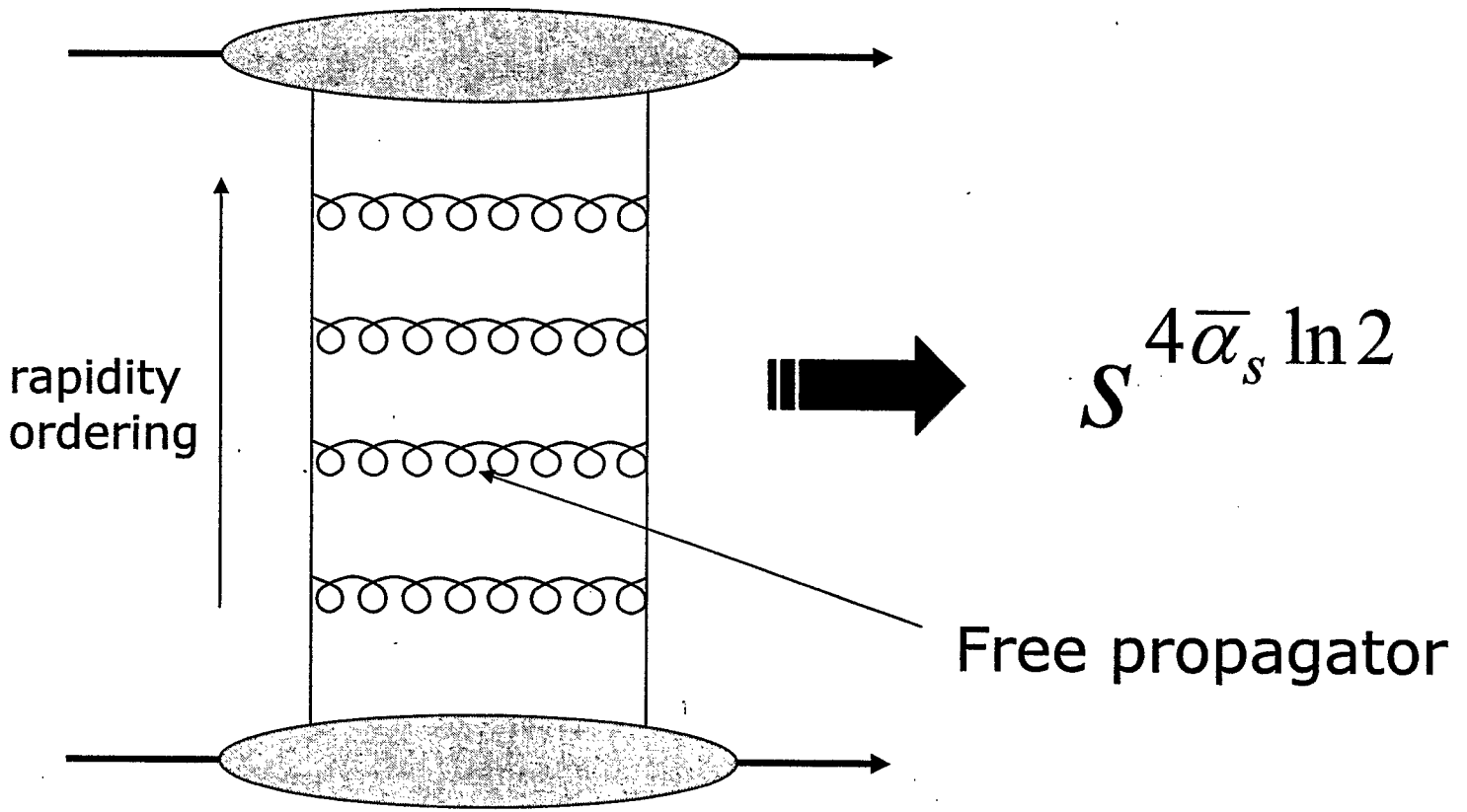
Effective action for high energy QCD with the Pomeron loop

Yoshitaka Hatta (RBRC)

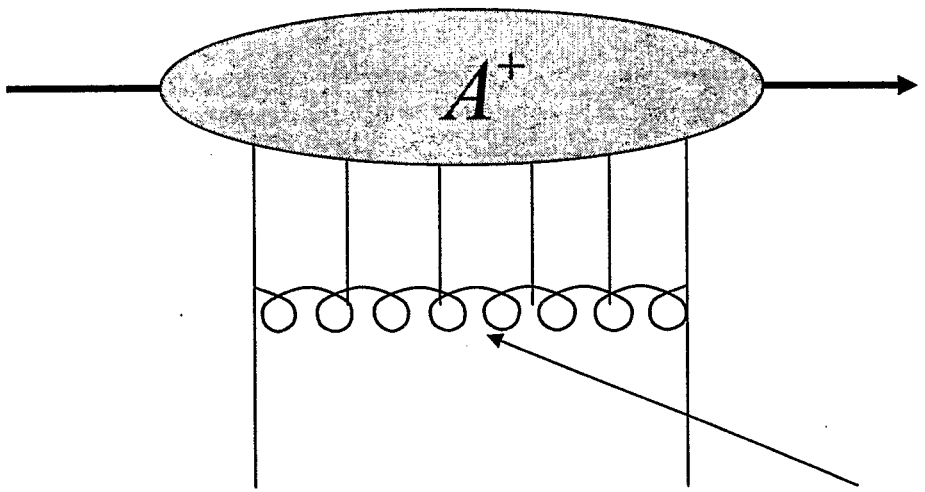
In collaboration with
E.Iancu, L.McLerran, A.Stasto,
D. Triantafyllopoulos
hep-ph/0504182,0505235
(NPA, in press)

QCD evolution equations at small-x

BFKL, BKP



Balitsky-Kovchegov-JIMWLK equation

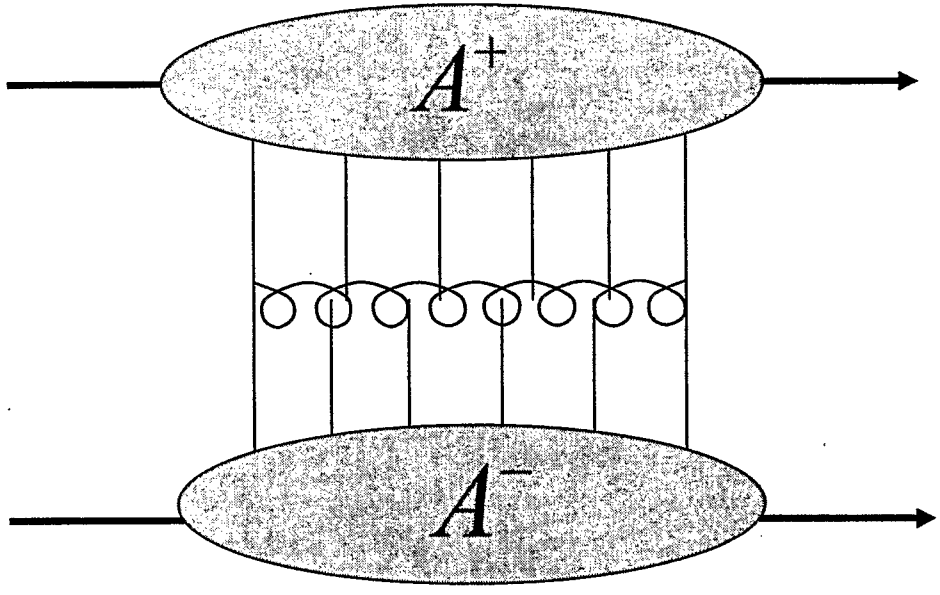


$$gA^+ \sim 1$$

Dressed propagator

Intended for dense-dilute scatterings.
Saturation at fixed impact parameter.
Total cross section still violates the Froissart bound.

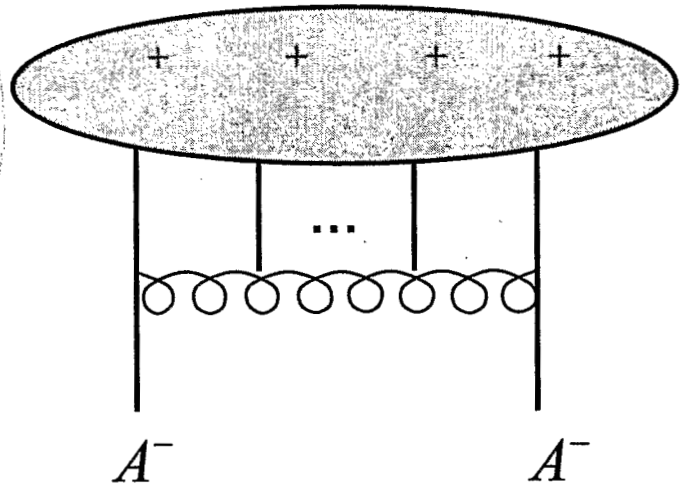
Beyond the B-JIMWLK^2 equation



An evolution equation with all possible reggeon number changing vertices describes both the gluon recombination and the gluon multiplication, namely, Pomeron loops.

Effective action approach

Lipatov, Verlinde bros, Balitsky...



Effective action

$$S_{\text{JIMWLK}} = A^- \eta[V, V^+] A^-$$

$$V^+ = \mathrm{P}\exp(ig \int dx^- A^+)$$

Kernel of the evolution equation

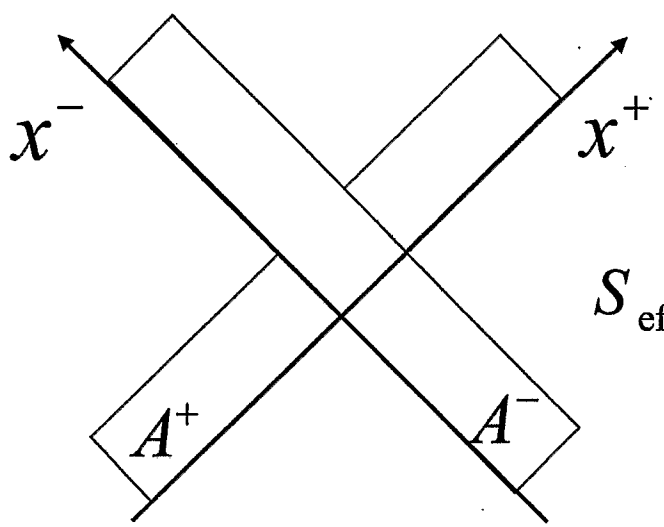
$$K_{\text{JIMWLK}} = \frac{\delta}{\delta A^+} \eta[V, V^+] \frac{\delta}{\delta A^+}$$

The complete kernel which contains Pomeron loops must be self-dual, i.e., invariant under $A^+ \leftrightarrow \frac{\delta}{\delta A^+}$.
(Kovner&Lublinsky,05)

Construction of the effective action

The total gauge field $\underset{\text{classical}}{A^+} + \underset{\text{semi-hard}}{a^\mu} + \underset{\text{soft}}{\delta A^-}$

$$\exp\left(iS_{\text{eff}}[A,\delta A]\right) = \int_{b\Lambda^+}^{\Lambda^+} Da \exp\left(iS_{\text{YM}} - iJ^\mu A_\mu + iS_{\text{WZ}}\right)$$



$$S_{\text{eff}} = -\frac{1}{2}\int_{xy} (D_\nu F^{\nu i})^a_x G^{ij}_{ab}(x,y)(D_\lambda F^{\lambda j})^b_y$$

Background field propagator in the light cone gauge

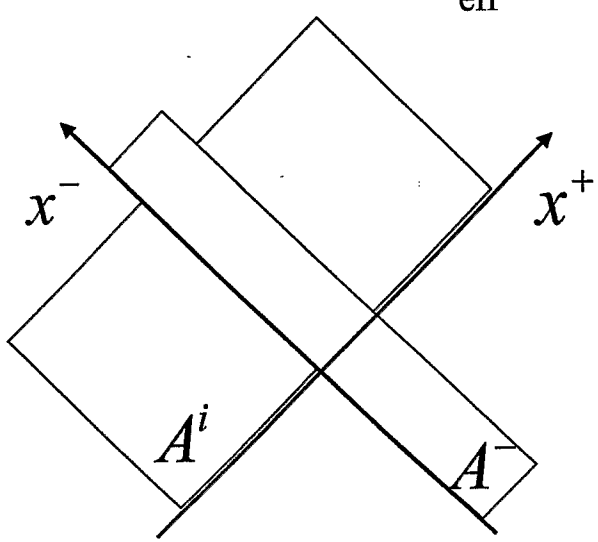
$$iG(x,y;\delta A^-) \propto \ln\frac{1}{b}\delta(x_T - y_T)\left[\theta(x^+ - y^+)W_{x^+,y^+}(x_T) + \theta(y^+ - x^+)W_{y^+,x^+}(x_T)\right]$$

$$W = T\exp(-\int dx^+ \frac{\delta}{\delta A^+})$$

$$S_{\text{eff}} = -\frac{1}{2}\int_{xy}(2D_+F^{+i})^a_x G^{ij}_{ab}(x,y;A^i,A^-)(2D_+F^{+j})^b_y$$

All order in $\frac{\delta}{\delta A^+}$

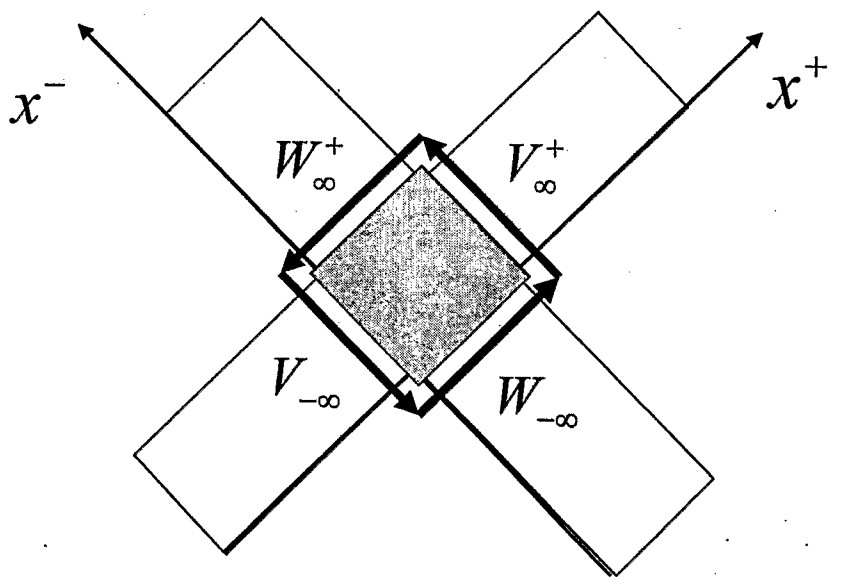
All order in A^+



Integration over $x^\pm$ leads to a 2D nonlinear sigma model.

Two-dimensional effective theory of Wilson lines

$$S_{\rm eff} = \frac{i}{2\pi g^2 N_c} \ln \frac{1}{b} \int_{\boldsymbol{x}} {\rm Tr}\Big[V_\infty^\dagger (\partial^i W_{-\infty})(\partial^i V_{-\infty}) W_\infty^\dagger + V_\infty^\dagger W_{-\infty} (\partial^i V_{-\infty})(\partial^i W_\infty^\dagger)$$
$$+ (\partial^i W_\infty^\dagger)(\partial^i V_\infty^\dagger) W_{-\infty} V_{-\infty} + W_\infty^\dagger (\partial^i V_\infty^\dagger)(\partial^i W_{-\infty}) V_{-\infty} \Big]$$



$$V_\infty^\dagger W_{-\infty} V_{-\infty} W_\infty^\dagger = 1$$

zero curvature

$S_{\rm eff}$ is invariant under $V^+ \leftrightarrow W$, i.e., $S_{\rm eff}$ is self-dual.

Summary

- B-JIMWLK^2 equation misses Pomeron loops. Necessity to construct a self-dual kernel.
- We constructed an important contribution to the complete kernel by combining the CGC and the effective action approaches.
- There are other diagrams still to be calculated to obtain the complete kernel.

Feedback Effects on the Pairing Interaction in Color Superconductors

Kei Iida
(Presented by Kenji Fukushima)

Feedback effects on the pairing interaction in color superconductors

Kei Iida (RIKEN BNL Research Center)
presented by Kenji Fukushima

Contents

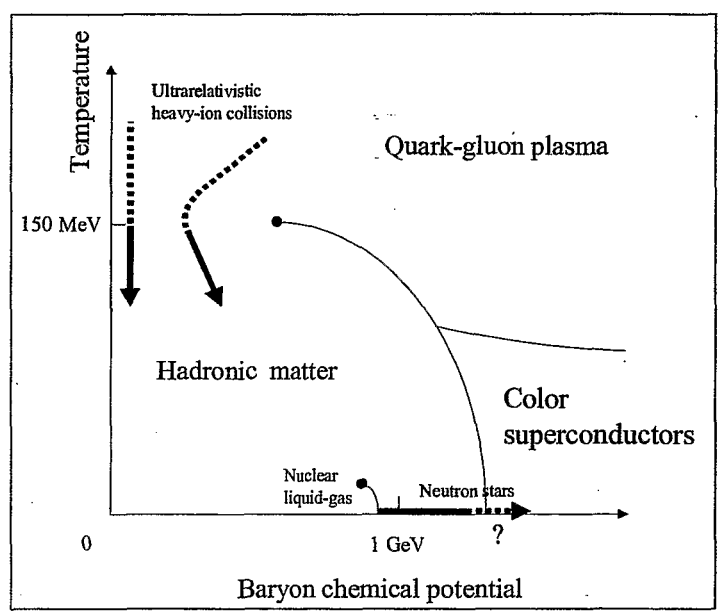
1. Introduction
2. Gap equation in weak coupling
3. Gap equation with feedback effects
4. Ginzburg-Landau theory: strong coupling corrections
5. Conclusion

Reference

KI, hep-ph/0507161 (to appear in PRD).

Introduction

QCD phase diagram



Crucial features of color superconductors

Superfluidity

— presence of a condensate of quark Cooper pairs and superfluid baryon density (n_s)

Color Meissner effects

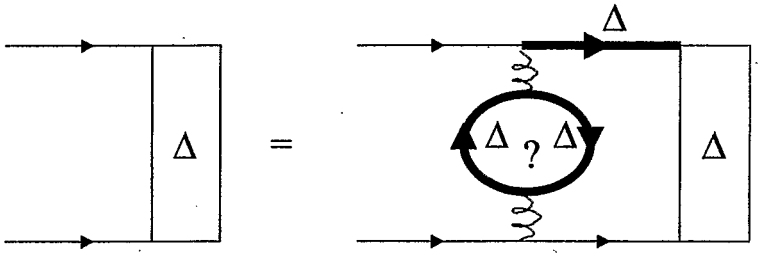
— transverse color fields screened in a spatial scale of order the London penetration depth ~ $(\mu / g^2 n_s)^{1/2}$

Introduction (contd.)

What happens if quark matter occurs in compact stars

Possible color superconductivity — *strong coupling regime*

How is the feedback correction to the weak coupling pairing gap?



Study of this correction is limited to the case of zero temperature
[order-of-magnitude estimates by Rischke, PRD **64** (2001) 094003].

Focus of this work

Feedback corrections near the transition temperature
— dominated by the color Meissner screening of the long-range magnetic force
— altering the gap magnitude in a different way among different phases

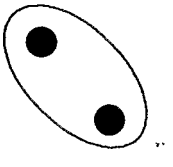
Introduction (contd.)

System

massless quarks of *uds* flavors and ***RGB*** colors
Fermi momenta common to all colors and flavors

Cooper pairing between quarks

parity	chirality	J	color	flavor
even	*LL*, *RR*	zero	antisymmetric	antisymmetric



On-shell gap at relative pair momentum $|\mathbf{k}|=k_F$

$$(\phi_+)_{abij} = \varepsilon_{abc}\varepsilon_{ijl}(\mathbf{d}_c)_l$$

a,b: colors of paired quarks
i,j: flavors of paired quarks
$\mathbf{d}_c$: complex vector in flavor space

Two optimal states

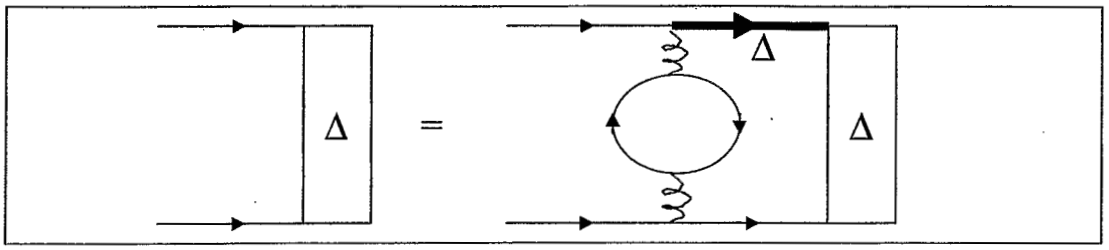
·Color-flavor locked (CFL) state

$$\mathbf{d}_R^* \cdot \mathbf{d}_G = \mathbf{d}_G^* \cdot \mathbf{d}_B = \mathbf{d}_B^* \cdot \mathbf{d}_R = 0,\ |\mathbf{d}_R| = |\mathbf{d}_G| = |\mathbf{d}_B| \qquad \text{("isotropic")}$$

·2 flavor color superconducting (2SC) state

$$\mathbf{d}_R \parallel \mathbf{d}_G \parallel \mathbf{d}_B \qquad \text{("anisotropic")}$$

Gap equation in weak coupling

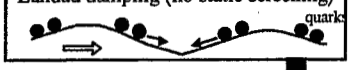


Gluon propagator (in Landau gauge)

For $|p_0| \ll |\mathbf{p}| \ll \mu$ (forward scattering),

$$D^{\alpha\beta}_{\mu\nu}(p) \cong -\frac{\delta_{\alpha\beta}P^T_{\mu\nu}}{|\mathbf{p}|^2 - i\pi\, m_{\mathrm{D}}^2 p_0/4|\mathbf{p}|} - \frac{\delta_{\alpha\beta}P^L_{\mu\nu}}{|\mathbf{p}|^2 + m_{\mathrm{D}}^2}, \quad m_{\mathrm{D}}^2 \cong \frac{N_{\mathrm{f}} g^2 \mu^2}{18\pi^2}$$

Landau damping (no static screening)



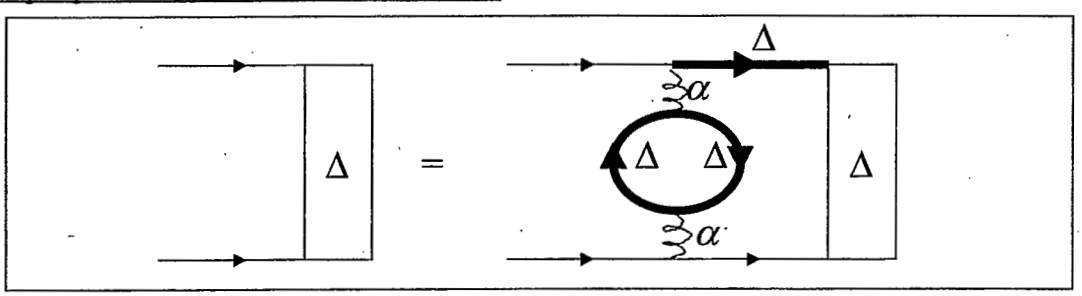
Debye screening

Gap equation for 2SC near T_c

$$d_F = \left(1 - \frac{\pi\bar{g}}{2}\frac{T - T_c}{T_c}\right) d_F - \frac{7\zeta(3)\bar{g}}{16\pi T_c^2} d_F^3 + O(d_F^5), \quad \bar{g} = \frac{g}{3\sqrt{2}\pi}$$

- Cf. The CFL state is more favorable than the 2SC state in weak coupling.

Gap equation with feedback corrections



Gluon propagator near T_c (in Landau gauge)

For $|p_0| \ll |\mathbf{p}| \ll \mu$ (forward scattering),

$$D^{\alpha\beta}_{\mu\nu}(p) \cong -\frac{\delta_{\alpha\beta}P^T_{\mu\nu}}{|\mathbf{p}|^2 - i\pi\, m_{\mathrm{D}}^2 p_0/4|\mathbf{p}| + (m_M^\alpha)^2 f(\mathbf{p})} - \frac{\delta_{\alpha\beta}P^L_{\mu\nu}}{|\mathbf{p}|^2 + m_{\mathrm{D}}^2 - 3(m_M^\alpha)^2 h(\mathbf{p})}, \quad m_{\mathrm{D}}^2 \cong \frac{N_{\mathrm{f}} g^2 \mu^2}{18\pi^2}$$

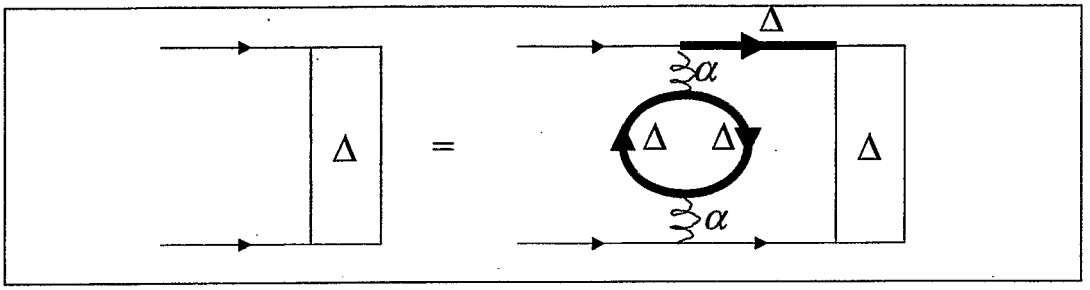
Meissner screening

with BCS kernel $f(\mathbf{p}) = \dfrac{6}{7\zeta(3)} \displaystyle\sum_{s=0}^{\infty} \int_0^1 dx \frac{1-x^2}{(s+1/2)\left[4(s+1/2)^2 + (|\mathbf{p}|x/2\pi T_c)^2\right]}$

$$\to \begin{cases} 1, & |\mathbf{p}| \ll T_c \text{ (London limit)} \\ 3\pi^4 T_c / 14\zeta(3)|\mathbf{p}|, & |\mathbf{p}| \gg T_c \text{ (Pippard limit)} \end{cases}$$

Cf. The gluon momenta $\mathbf{p}$ of order T_c are most important for the feedback effects.

Gap equation with feedback corrections (contd.)



Meissner screening

α	2SC Meissner mass	2SC color pairing force	CFL Meissner mass
1-3	0	*attractive*	+
4-7	+	*none*	+
8	+	*repulsive*	+

Feedback effects near T_c

to leading order in g, the 2SC gap increases by a factor of $(1-C\bar{g}/2)^{-1/2}$, $C=0.409\ldots$
the CFL gap decreases by a factor of $(1+3C\bar{g})^{-1/2}$

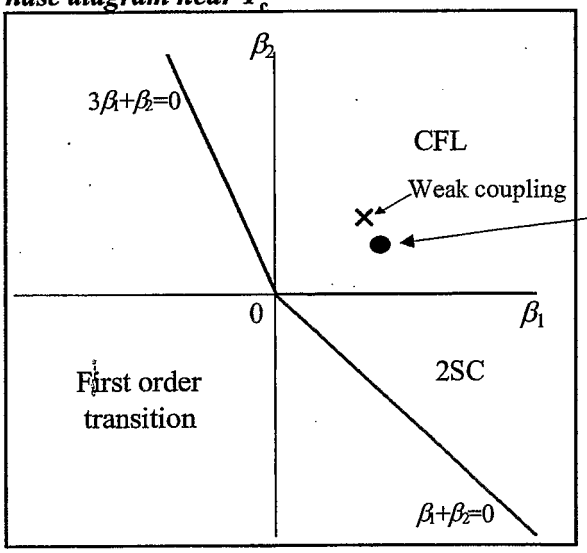
Ginzburg-Landau theory

Ref. Iida & Baym, PRD **63** (2001) 074018; **66** (2002) 059903(E).

Ginzburg-Landau free energy

$$\Delta\Omega \equiv \Omega_s - \Omega_n = \bar{\alpha}\sum_a |\mathbf{d}_a|^2 + \beta_1\left(\sum_a |\mathbf{d}_a|^2\right)^2 + \beta_2 \sum_{ab} |\mathbf{d}_a^* \cdot \mathbf{d}_b|^2$$

Phase diagram near T_c



Strong coupling corrections

$$\beta_1 = \frac{7\zeta(3)}{8(\pi T_c)^2}\left(1+\frac{13}{2}C\bar{g}\right)N\left(\frac{\mu}{3}\right)$$

$$\beta_2 = \frac{7\zeta(3)}{8(\pi T_c)^2}\left(1-\frac{15}{2}C\bar{g}\right)N\left(\frac{\mu}{3}\right)$$

$$\bar{\alpha} = 4N\left(\frac{\mu}{3}\right)\frac{T-T_c}{T_c}$$

with $N\left(\frac{\mu}{3}\right)=\frac{1}{2\pi^2}\left(\frac{\mu}{3}\right)^2$, $T_c=\frac{1812.3\cdots}{g^5}\frac{\mu}{3}\exp\left(-\frac{3\pi^2}{\sqrt{2}g}\right)$

Corrections are of order $\log^{-1}(\mu / T_c)$ rather than T_c/μ as encountered in ^{3}He.

Conclusion

The feedback role that the gap dependence of the pairing interaction plays in the gap equation for color superconductors near T_c

- dominated by the color Meissner screening of the long-range transverse force
- increasing the 2SC gap, while decreasing the CFL gap

  —— complicated color dependence of the Meissner-screened pairing force

- leading to strong coupling corrections to the parameters characterizing the fourth order terms in the Ginzburg-Landau free energy

  —— of order $g \sim \log^{-1}(\mu / T_c)$ due to the long-range nature of the pairing force

Phase Structure and Instability in Dense Quark Matter

Kenji Fukushima

Phase Structure and Instability in Dense Quark Matter

Kenji Fukushima
(RIKEN BNL Research Center)

Ref: K.Fukushima hep-ph/0506080 to appear in PRD

October 2005

Simple Questions

- What happens eventually when matter is heated and heated ?

  ➡ **Quark-Gluon Plasma**

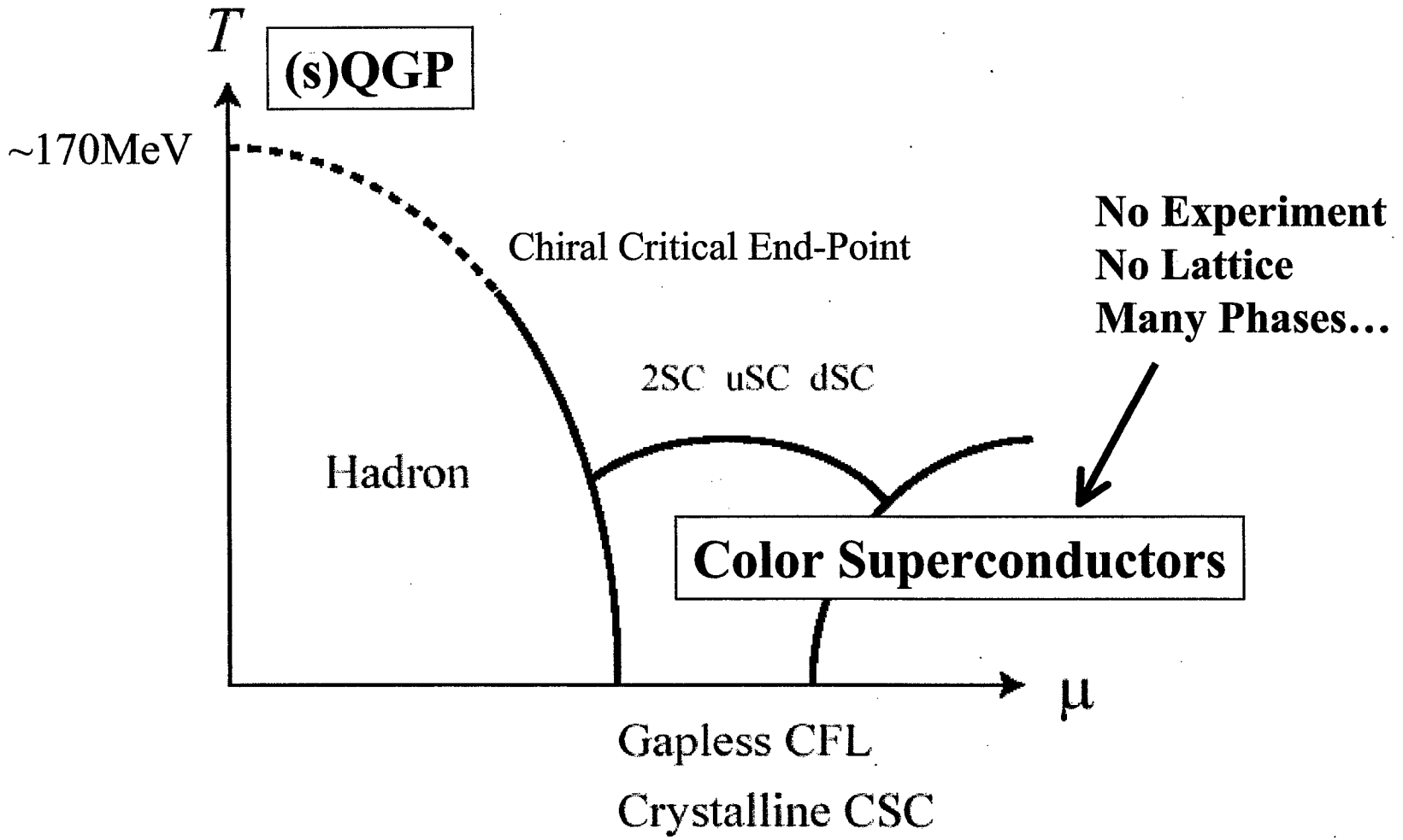
  in Relativistic Heavy-Ion Collisions

- What happens eventually when matter is squeezed and squeezed ?

  ➡ **Color Superconductor**

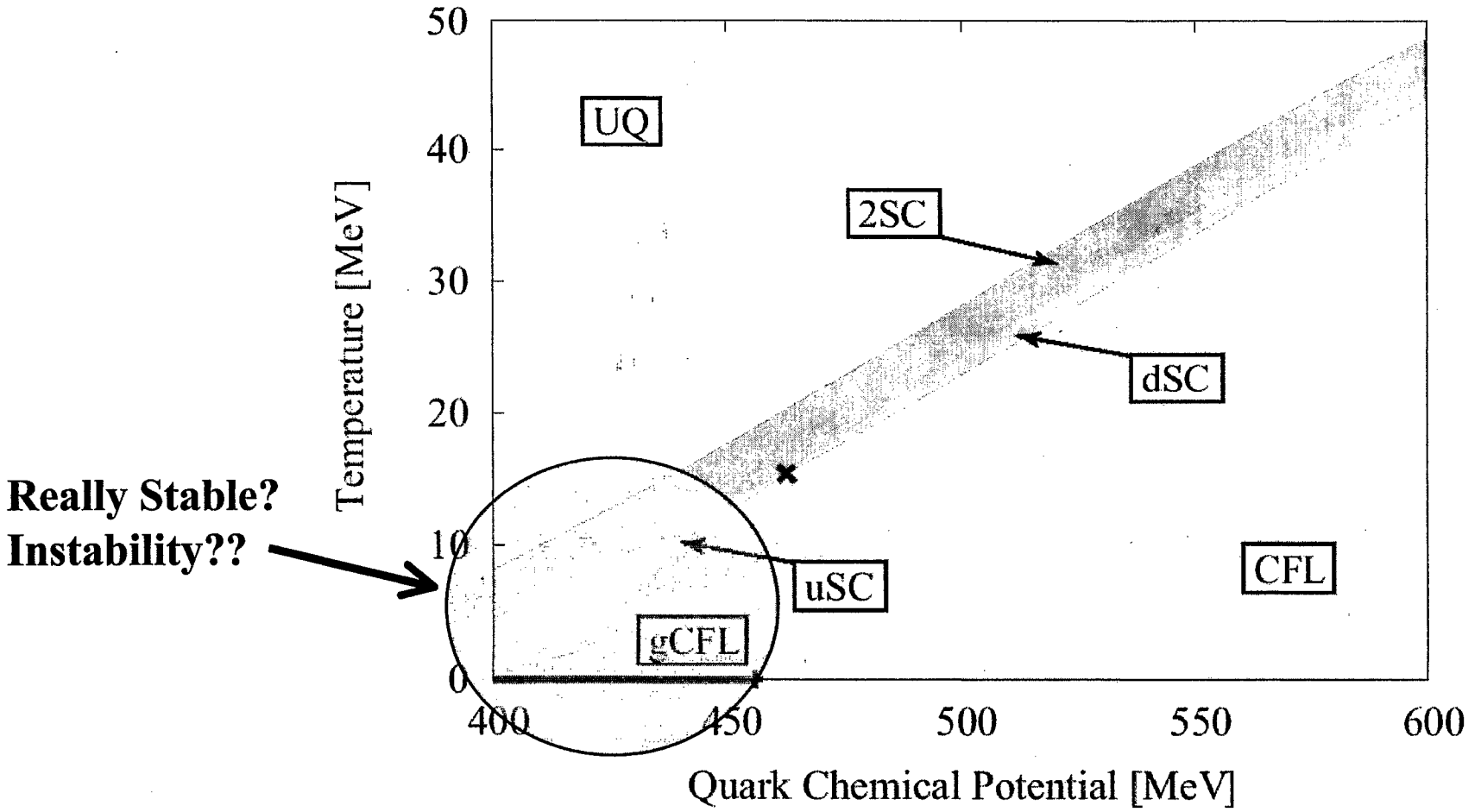
  in the cores of compact stellar objects

Conjectured QCD Phase Diagram



October 2005

Phase Diagram at High Density



Cooper Pairing Pattern

Diquark Condensate

$$\Delta_{\alpha i} \propto \varepsilon_{\alpha\beta\gamma}\varepsilon_{ijk}\left\langle \overline{\psi}_{\beta j} i\gamma_5 C \overline{\psi}^{\mathrm{T}}_{\gamma k} \right\rangle$$

Anti-symmetric in Color (attractive in OGE)
Anti-symmetric in Flavor, Positive Parity (energetically)
Anti-symmetric in Spin

Color-Flavor Locking $\Delta_{\alpha i} = \delta_{\alpha i}\Delta_i$ analogous to the ^{3}He B phase

$\Delta_s \rightarrow \Delta_{ud}$ (or Δ_3)	Δ_{ds} (or Δ_1)	Δ_{su} (or Δ_2)
$ru - gd$	$gd - bs$	$bs - ru$
$gu - rd$	$bd - gs$	$rs - bu$

Family of Color Superconductors

$\Delta_{ud}, \Delta_{ds}, \Delta_{su} \neq 0$ Color - Flavor Locked (CFL) Phase

$\Delta_{ds} = 0, \quad \Delta_{su}, \Delta_{ud} \neq 0$ uSC

$\Delta_{su} = 0, \quad \Delta_{ds}, \Delta_{ud} \neq 0$ dSC

$\Delta_{ds} = \Delta_{su} = 0, \quad \Delta_{ud} \neq 0$ 2SC

$\Delta_{ud} = \Delta_{ds} = \Delta_{su} = 0$ UQM

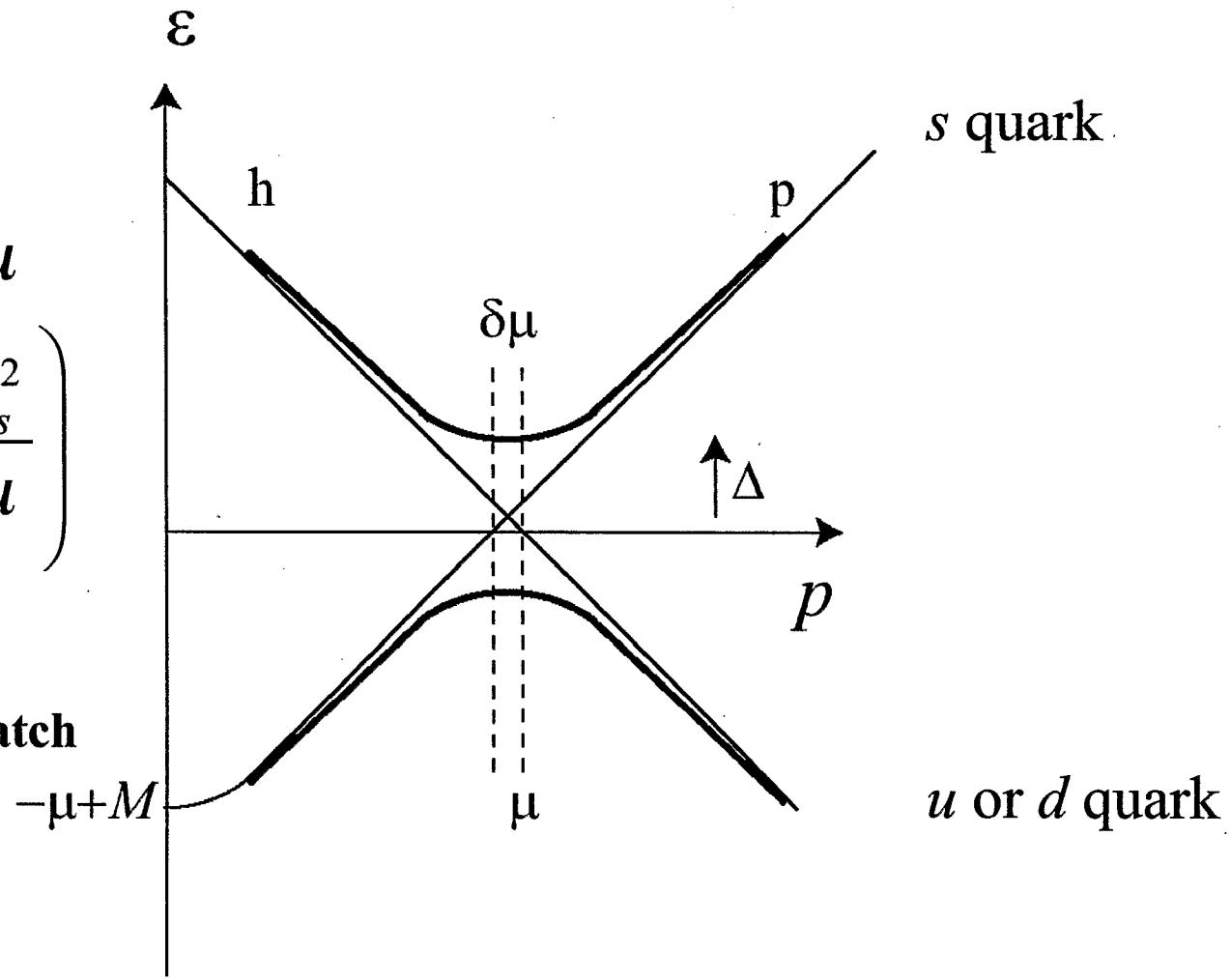
Effect of Non-Zero M_s

$M_s \neq 0$

$$\sqrt{p^2 + M_s^2} - \mu$$

$$\approx p - \left(\mu - \frac{M_s^2}{2\mu} \right)$$

Fermi Surface Mismatch



Gapless Superconductor

Gapless dispersion appears when $\delta\mu > 2\Delta$

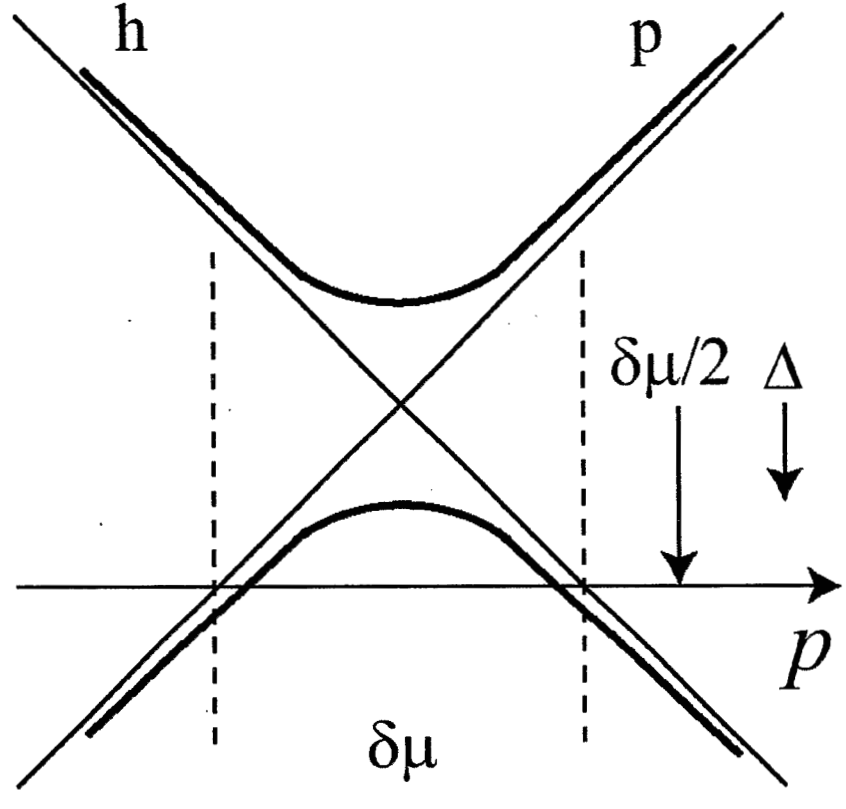
CFL

↓

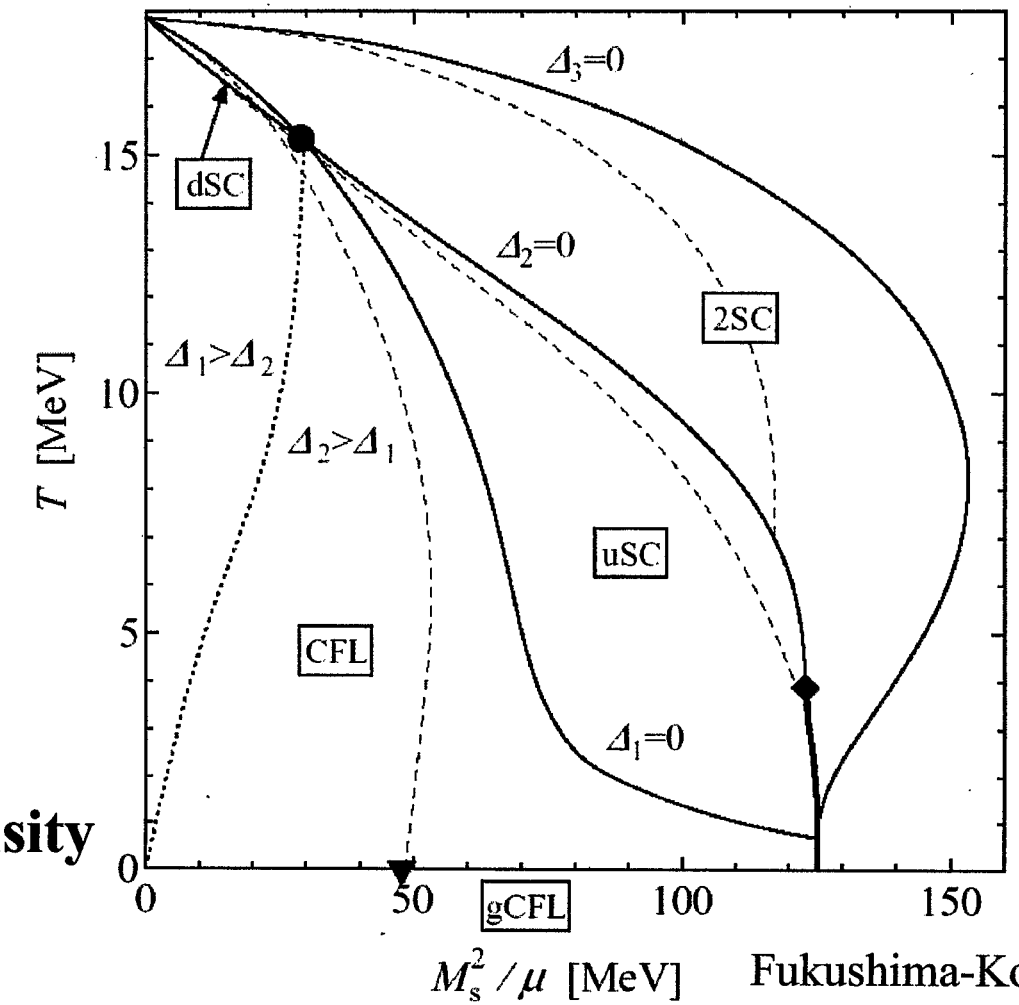
gapless CFL (gCFL)

This happens for Δ_{ds} pairing, which makes Δ_{ds} disfavored. Δ_{ds} vanishes first → uSC

Unstable???



Phase Structure

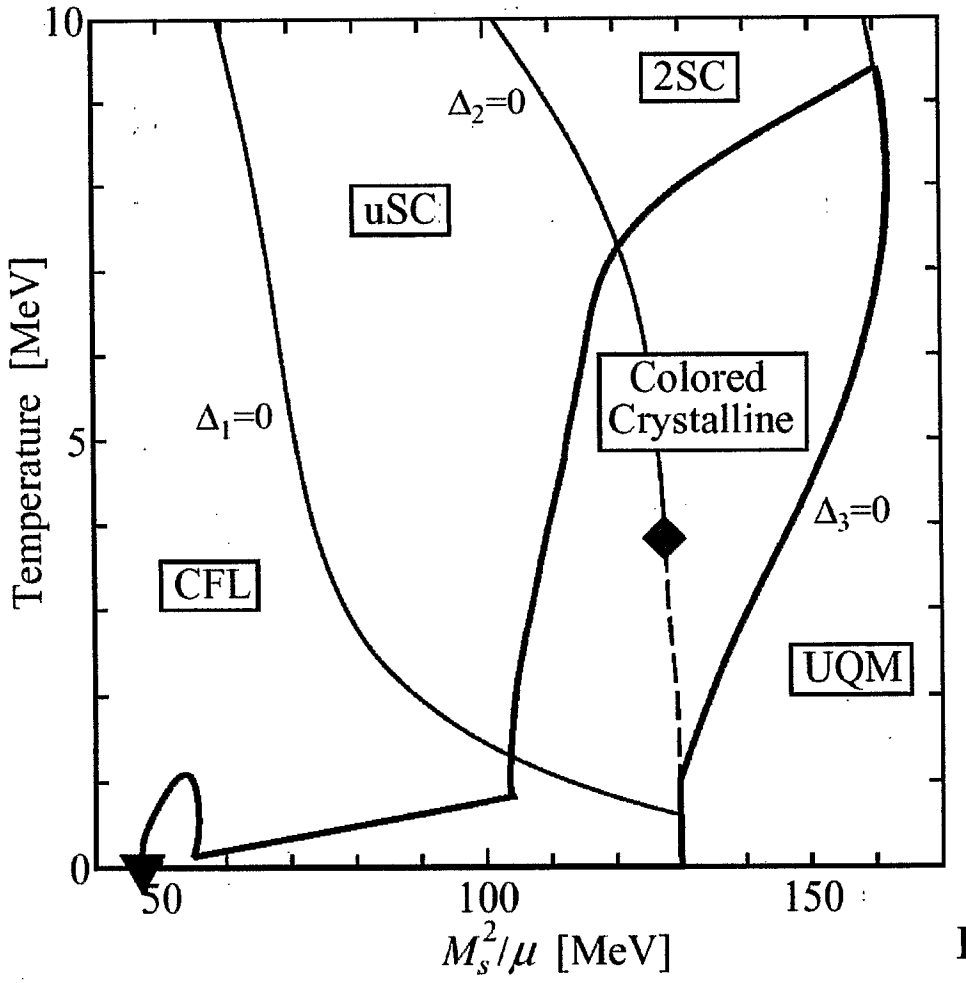


High Density

Low Density

Fukushima-Kouvaris-Rajagopal ('04)

Unstable Regions

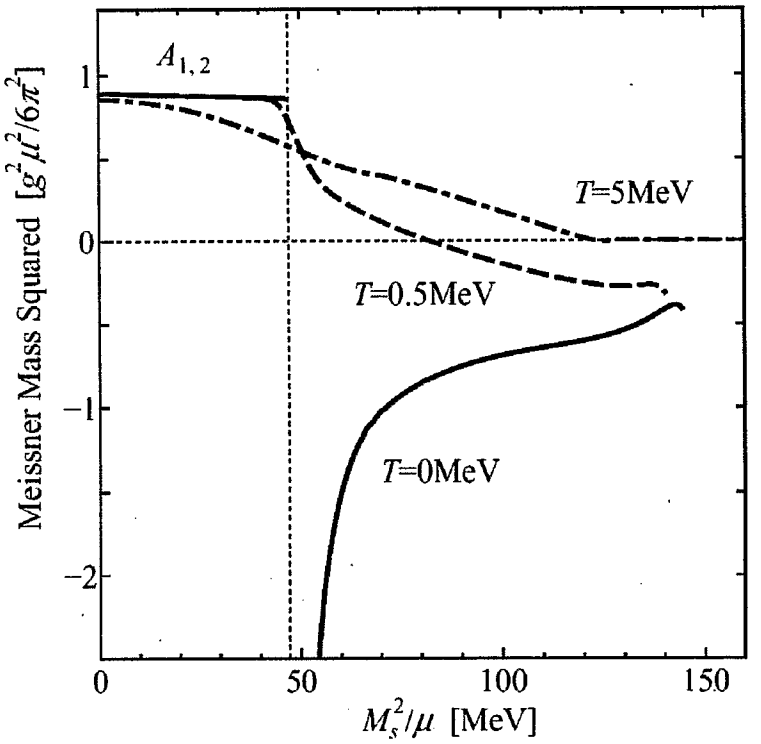


Fukushima ('05)

Chromomagnetic Instability

Meissner Screening Mass

In CFL (global) color symmetry is all broken → All gluons are massive.

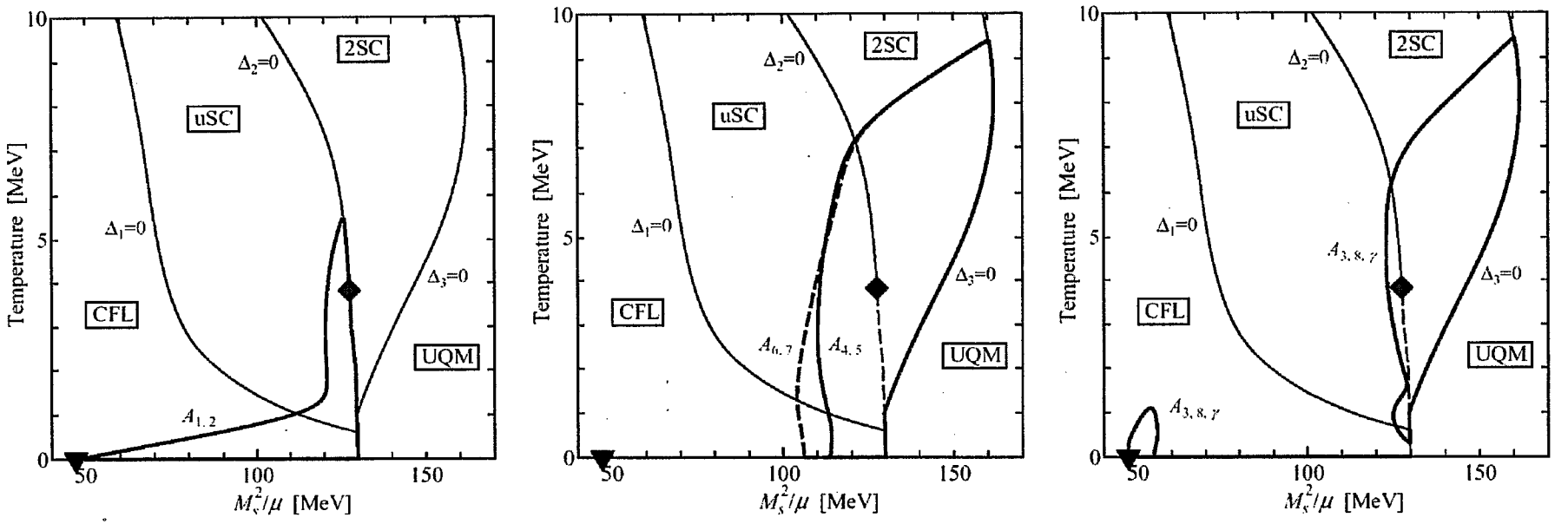


Meissner mass is imaginary in the gCFL phase, especially at low temperatures.

↑

Gapless Quarks

Unstable Regions



Instability for A_1 and A_2

Instability for A_3 and A_8 and A_γ

Instability for A_4 and A_5 (solid)
Instability for A_6 and A_7 (dashed)

Fukushima ('05)

Summary

- Chromomagnetic instability in three-flavor quark matter has been analyzed.
- Meissner screening mass for respective gluons has been calculated.
- gCFL is not stable at all!
  uSC and 2SC have unstable regions.
- Unstable regions are mapped onto the phase diagram including (g)CFL, uSC, (g)2SC.
- Phase boundaries toward the LOFF states.

Charm Mesons with DWF Quarks on a Quenched 3 GeV Lattice

Shigemi Ohta

Charm mesons with DWF quarks on a quenched 3 GeV lattice

HueyWen Lin,* Shigemi Ohta,† and Norikazu Yamada§ [RBC collaboration]

Abridged from SO's talk in September 15, 2005, Computational Hadron Physics Workshop, University of Cyprus, Nicosia

Preliminary report on RBC spectroscopy calculations on a DBW2 quenched gauge ensemble,

- at lattice cutoff a^{-1} of about 3 GeV,
- all the quarks represented by domain-wall fermions (DWF),
- D and D_s mesons with $J^P = 0^-$, 1^-, 0^+ and 1^+:
  - masses well reproduced to within a few %,
  - splittings Δ_J between parity partners over estimated by 10-20 %,
  - only 60-65 % of hyperfine splittings reproduced,
  - 0^- decay constant f_D within experimental error and f_{D_s} encouraging.
- charmonia analyses exist as well, with $J^P = 0^-$, 1^-, 0^+ and 1^+ (but not today.)

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§Inst. Particle and Nuclear Studies, KEK and Physics Department, Sokendai, Tsukuba, Ibaraki 305-0801, Japan

Charm as DWF: originally investigated for kaon matrix elements with "charm-in" using DWF.

- Nori pushed it further for test of various heavy quark schemes, and D and D_s meson spectroscopy.
- HueyWen is pushing a relativistic scheme under supervision by Norman Christ.

Here we use a combination of DWF quark and DBW2 gluon actions:

- DWF (domain wall fermions) preserves almost exact chiral symmetry, and
- DBW2 ("doubly blocked Wilson 2") action improves approach to the continuum.

The combination allows us to have

- good chiral behavior, *i.e.* close enough to the continuum, and
- sufficiently large volume.

Recent discoveries of D and D_s meson excited states provide an interesting target for DWF charm.

Mass:

charm-nonstrange

J^P	mass (MeV)
$D^{\pm}(0^-)$	1869.4(5)
$D^{*\pm}(1^-)$	2010.0(5)
$D_0^*(0^+?)$	2308(17)(15)(28)
$D_1'(1^+)$	2427(26)(20)(15)

charm-strange

J^P	mass (MeV)
$D_s^{\pm}(0^-)$	1968.3(5)
$D^{*\pm}(1^-?)$	2112.1(7)
$D_{s0}^{*\pm}(0^+)$	2317.4(9)
$D_{s1}^{*\pm}(1^+)$	2459.3(1.3)

Splittings:

between parities Δ_{qJ}

light quark	$0^+ - 0^-$ (MeV)	$1^+ - 1^-$ (MeV)
s	349.1	347.2
ud	439	417

- insensitive to J, $\Delta_{q0} \sim \Delta_{q1}$,
- m_l dependent, $\Delta_{ud} > \Delta_s$.

"hyperfine" $\Delta_{\rm hf}$

light quark	$1^- - 0^-$ (MeV)	$1^+ - 0^+$ (MeV)
s	143.8	141.9
ud	140.6	119

- independent of m_l or parity.

Model studies:

- Before the discoveries, Bardeen, Eichten and Hill[1] predicted this
  - based on their $SU(3)_L \times SU(3)_R$ symmetry for heavy-light systems.
  - $\Delta_J \sim 350$MeV is weakly dependent on the heavy quark mass: $\Delta_J = \Delta_J(m_{\text{heavy}})$.
  - A Goldberger-Treiman like relation in the pion emission from the positive-parity states, $g_\pi = \Delta_J / f_\pi$.
- Afterwards, Nowak, Rho and Zahed[2] made similar prediction from a different view point.
- Becirevic, Fajfer and Prelovsek[3] discussed Δ_J dependence on the light quark mass,
  - found $\Delta_{ud,J} > \Delta_{s,J}$ is difficult to understand.

[1] W. A. Bardeen, E. J. Eichten and C. T. Hill, Phys. Rev. D **68**, 054024 (2003) [arXiv:hep-ph/0305049].
[2] M. A. Nowak, M. Rho and I. Zahed, Acta Phys. Polon. B **35**, 2377 (2004) [arXiv:hep-ph/0307102].
[3] D. Becirevic, S. Fajfer and S. Prelovsek, Phys. Lett. B **599**, 55 (2004) [arXiv:hep-ph/0406296].

Earlier lattice works:

- Peter Boyle (UKQCD)[4] was the first to study these and other related states on the lattice.
  - Wilson gauge action at $\beta = 6.0$ and tadpole improved clover.
  - Hyperfine splittings scale well, lying significantly below their experimental values.
  - Overestimates Δ_J?
- NRQCD (J. Hein et al.)[5]:
  - $\sim$2 fm boxes at $\beta = 5.7$ and 6.2.
  - Overestimates Δ_J.
- Gunnar Bali[6]:
  - confirms earlier overestimates of Δ_J: (450-500)$\pm$50 MeV?
- MILC (M. di Pierro et al.)[7]: Fermilab heavy quark and MILC sea,
  - similar over estimation of Δ_J seen.
- UKQCD (A.M. Green et al)[8]: static heavy quark
  - Quenched and two-flavor dynamical configurations.
  - Weak dependence on light-quark mass?

[4] P. Boyle [UKQCD Collaboration], Nucl. Phys. Proc. Suppl. **63**, 314 (1998) [arXiv:hep-lat/9710036].
[5] J. Hein *et al.*, Phys. Rev. D **62**, 074503 (2000) [arXiv:hep-ph/0003130].
[6] G. S. Bali, Phys. Rev. D **68**, 071501 (2003) [arXiv:hep-ph/0305209].
[7] M. di Pierro *et al.*, Nucl. Phys. Proc. Suppl. **129**, 328 (2004) [arXiv:hep-lat/0310045].
[8] A. M. Green, J. Koponen, C. McNeile, C. Michael and G. Thompson [UKQCD], Phys. Rev. D **69**, 094505 (2004) [arXiv:hep-lat/0312007].

Earlier lattice works (continued):

- UKQCD (A. Dougall, R.D. Kenway, C.M. Maynard, C. McNeile)[9]:
  - Quenched Wilson gauge at $\beta = 5.93$, 6.0, 6.2; two-flavor clover at $\beta = 5.2$ and $\kappa_{\text{sea}} = 0.135$.
  - Δ for spin 0 and 1 are degenerate.

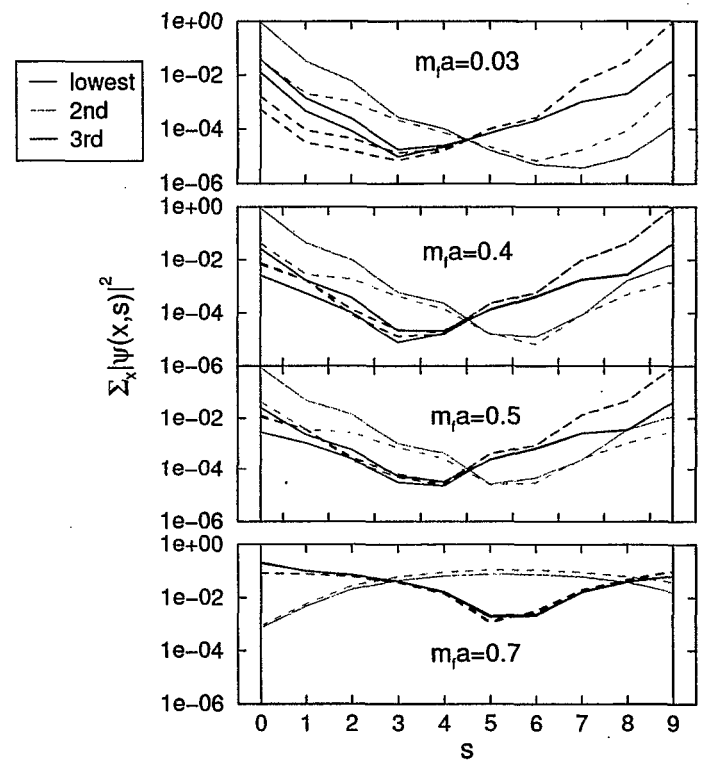
Earlier lattice works on decay constants:

- ALPHA (A. Juttner and J. Rolf)[10],improved Wilson: $f_{D_s} = 252(9)$ MeV.
- FNAL/MILC/HPQCD[11]: $f_D = 201(3)(17)$ MeV and $f_{D_s} = 249(3)(16)$ MeV with MILC 2+1 lattices.

[9] A. Dougall, R. D. Kenway, C. M. Maynard and C. McNeile [UKQCD], Phys. Lett. B **569**, 41 (2003) [arXiv:hep-lat/0307001].
[10] A. Juttner and J. Rolf, Nucl. Phys. Proc. Suppl. **129**, 319 (2004) [arXiv:hep-lat/0309069].
[11] C. Aubin *et al.*, arXiv:hep-lat/0506030.

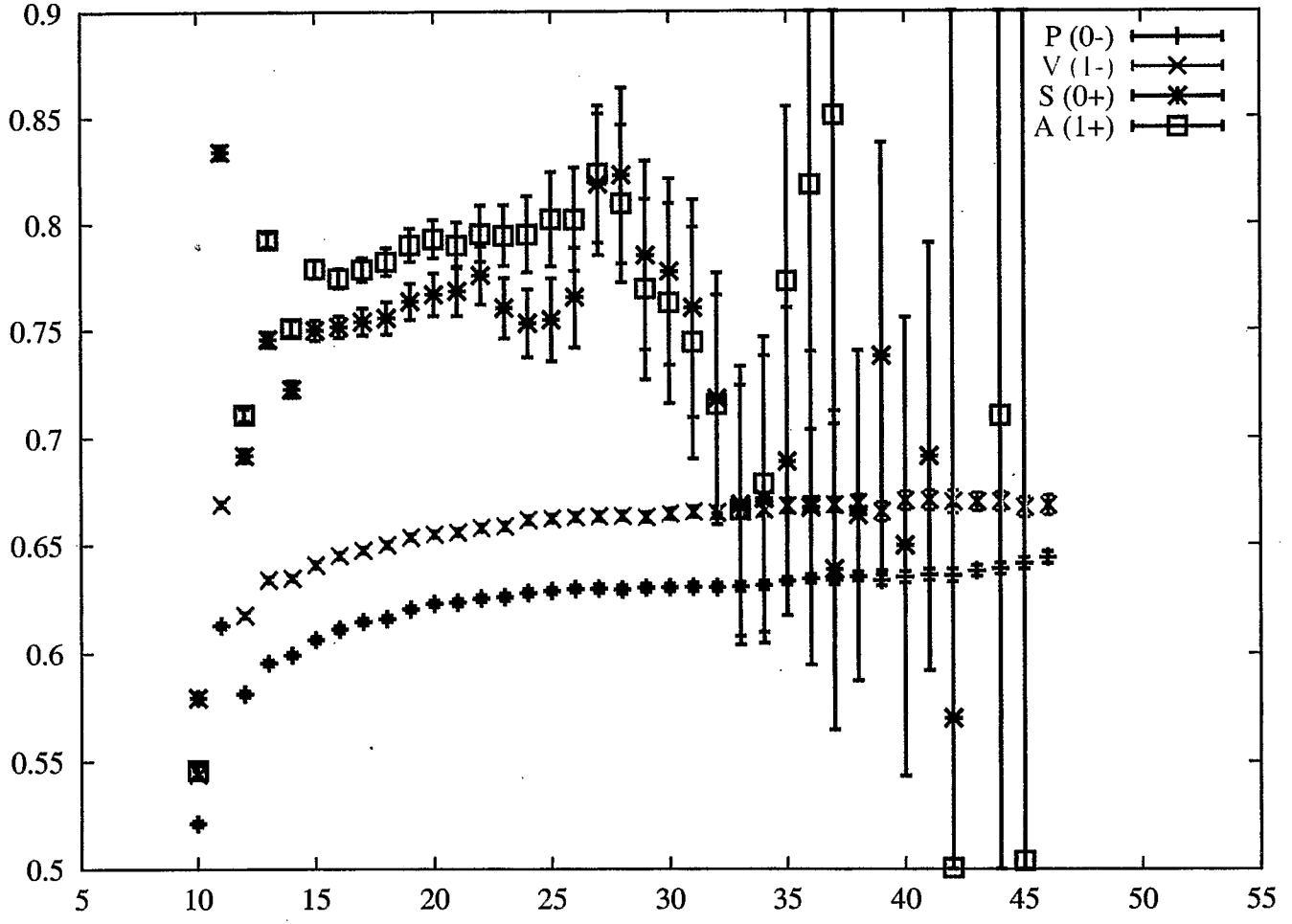
Advantages of domain-wall fermions (DWF):

- Describes light-quark chiral symmetry well: $O(a)$ error exponentially suppressed.
- Describes charm propagation on the lattice: $m_{\text{heavy}}a \sim 0.4 - 0.5$ still pegged.
- Present calculation:
  - quenched DBW2,
  - $\beta = 1.22$, $a^{-1} \sim 3\text{GeV}$,
  - $L_s = 10$, $M_5 = 1.65$,
  - $24^3 \times 48 \times 10$ ($\sim (1.6\text{fm})^3$) volume,
  - $m_{\text{light}}a = 0.08$, 0.016, 0.024, 0.032, and 0.040,
  - $m_{\text{heavy}}a = 0.1$, 0.2, 0.3, 0.4 and 0.5,
  - 103 configurations.



Allow explore both quark-mass dependences and Δ_{s0}-Δ_{s1} degeneracy.

Effective mass: e.g. $m_{\text{heavy}}a = 0.3$ and $m_{\text{light}}a = 0.040$,



reasonable plateaux allow meson mass extraction for all of $0^{\pm}$ and $1^{\pm}$.

Scales:

- known from previous RBC works[12] are,
  - lattice cutoff: $a^{-1} = 2.914(54)$ GeV set by m_ρ,
  - strange mass: $m_s a \sim 0.030$ set by m_K.
- charm mass: using the above and one of the following known meson mass,
  - $D_s(0^-)$: results in $m_c a = 0.35965$ we use this in the following,
  - η_c: 0.35595,
  - J/ψ: 0.37048.

Quenched systematics are of course expected.

[12] Y. Aoki *et al.*, arXiv:hep-lat/0508011.

D_s meson mass: preliminary results are

J^P	experiemnt (MeV)	this calculation (MeV)
$D_s^{\pm}(0^-)$	1968.3(5)	1968.3 (input)
$D^{*\pm}(1^-?)$	2112.1(7)	2055(6) (2.7% under)
$D_{s0}^{*\pm}(0^+)$	2317.4(9)	2380(30) (2.5% over)
$D_{s1}^{*\pm}(1^+)$	2459.3(1.3)	2460(40) (0.03% over)

in reasonable agreement with the experiments.

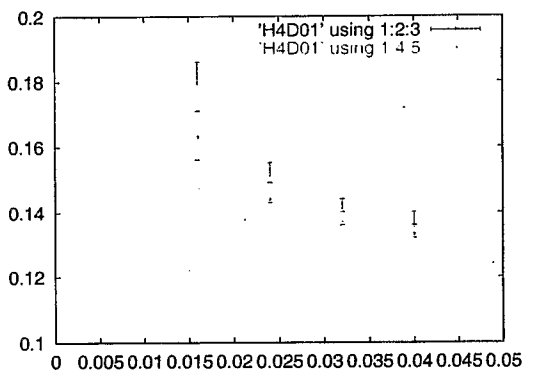
Parity splittings:

- $\Delta_{s,0} = 410(30)$ MeV, 18% over estimate compared with 349 MeV experiment,
- $\Delta_{s,1} = 380(20)$ MeV, 10% over estimate compared with 347 MeV experiment,

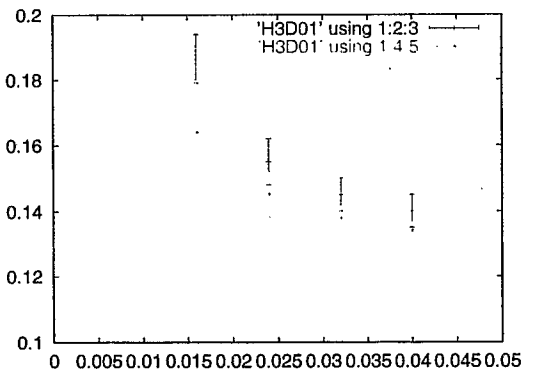
statistically degenerate and seem better than earlier lattice calculations.

Hyperfine splitting: about 87(6) MeV, reproduces about 60% of the 144 MeV experiment.

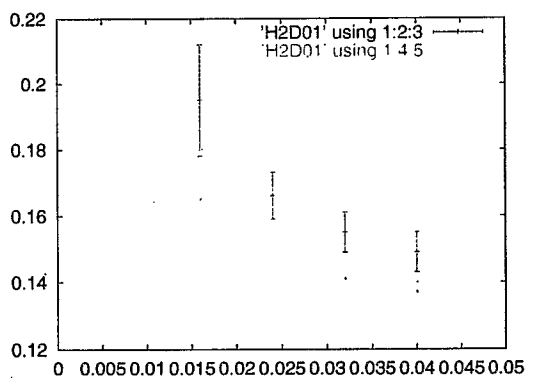
To summarize quark masss dependences of parity splittings:



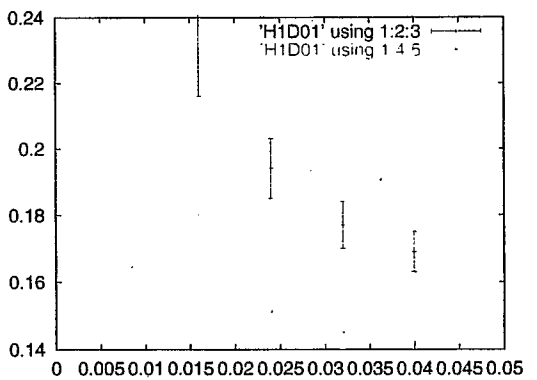
$m_{\text{heavy}}a = 0.4$



$m_{\text{heavy}}a = 0.3$



$m_{\text{heavy}}a = 0.2$



$m_{\text{heavy}}a = 0.1$

For dependence on m_{heavy}:

- seem statistically degenerate for $m_{\text{heavy}}a = 0.4$ and 0.3, but
- but $\Delta_{J=0} > \Delta_{J=1}$ for lighter m_{heavy}.

And on m_{light}: both increases toward lighter m_{light}.

D meson mass: extrapolate from $m_{\text{light}}a = 0.040$, 0.032, and 0.024, and 0.016 and 0.008 if possible. Preliminary results are

J^P	experiment (MeV)	this calculation (MeV)
$D^{\pm}(0^-)$	1869.4(5)	1876.7(1.2) (0.4% over)
$D^{*\pm}(1^-)$	2010.0(5)	1968(2) (2% under)
$D_0^*(0^+?)$	2308(17)(15)(28)	2362(20) (2.5% over)
$D_1'(1^+)$	2427(26)(20)(15)	2455(17) (1.2% over)

again in reasonable agreement with the experiments.

Parity splittings:

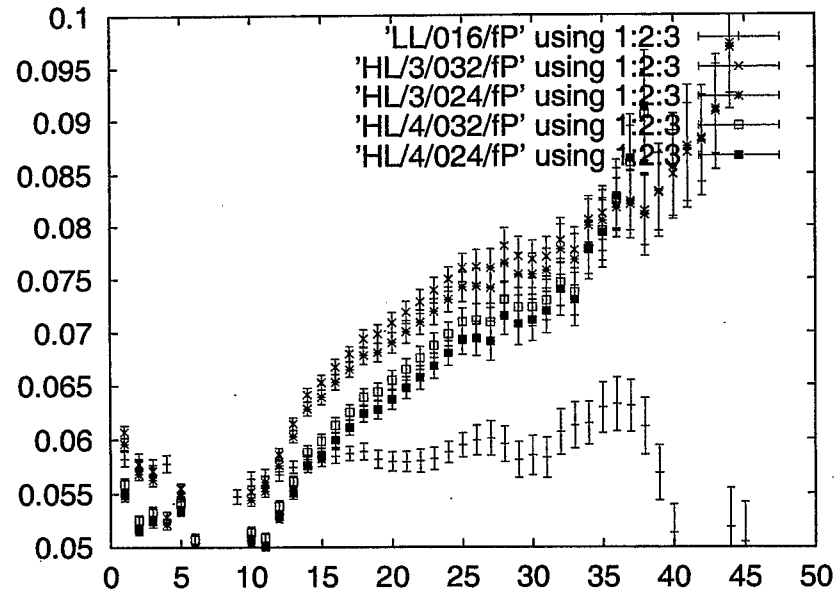
- $\Delta_{s,0} = 487(20)$ MeV, 11% over estimate compared with 439 MeV experiment,
- $\Delta_{s,1} = 490(17)$ MeV, 18% over estimate compared with 417 MeV experiment,

statistically degenerate.

Hyperfine splitting: about 91(2) MeV, reproduces about 65% of the 141 MeV experiment.

Pseudoscalar meson decay constant: $f_P = \dfrac{\langle \mathrm{vac}|A_t|P\rangle}{m_P}$.

We use a ratio $\dfrac{\mathcal{A}^{A_tP}_{\mathrm{point-wall}}}{\sqrt{\frac{m_P}{2}V\mathcal{A}^{PP}_{\mathrm{wall-wall}}}}$.



We obtain bare values of

- f_{D_s} of 0.0742(21) or 216(6) MeV by interpolation to $m_{\mathrm{strange}}a = 0.030$ and $m_{\mathrm{charm}}a = 0.360$
- f_D of 0.0696(7) or 203(2) MeV by linear extrapolation, or
- f_D of 0.0717(7) or 209(2) MeV by quadratic extrapolation.

We can use heavy-light current renormalization by Aoki, Kuramashi and Yamada:

$$Z_A^{HL} = Z_A^{LL,NP} \times \sqrt{Z_{\rm dw}(am_{\rm charm})/Z_{\rm dw}(0)},$$

where the tree-level domain-wall fermion wave function renormalization is given by

$$Z_{\rm dw}(am_f, \omega) = \frac{am_f[1+(am_f)^2]\cosh(m_p) - 2(am_f)^2\omega\sinh(am_p)}{[1-(am_f)^2]\sinh(am_p)},$$

and

$$Z_{\rm dw}(0) = \frac{1}{\omega(2-\omega)},$$

with $\omega = 2 - M_5$ and

$$am_p = \ln\left|\frac{-(am_f)\omega^2 + \sqrt{[1+(am_f)^2]^2 + (am_f)^2\omega^2(\omega^2-4)}}{1+(am_f)^2 - 2\omega(am_f)}\right|.$$

With $am_{\rm charm} = 0.36$, we obtain $\sqrt{Z_{\rm dw}(am_{\rm charm})/Z_{\rm dw}(0)} = 1.1834$, and accordingly

$$Z_A^{HL} = 1.0509$$

with $Z_A^{LL,NP} = 0.888$.

Preliminary renormalized values are: $f_{D_s} = 226(6)$ MeV and $f_D = 212(2)$ (lin.) or $219(2)$ MeV (quad.). Experimentally, $f_D = 230(42)(10)$ MeV and $f_{D_s} = 266(32)$ MeV.

Summary: we are studying charm-light systems with DWF and $a^{-1} \sim 2.914(54)$ GeV gauge ensemble.

- DWF seems able to describe charm on quenched DBW2 ensemble at this cutoff,
- With $m_{\text{strange}}a = 0.030$ and $m_{\text{charm}}a = 0.36$,
  - $J^P = 0^\pm$ and $1^\pm$ D and D_s meson masses are well reproduced to within a few %,
  - parity splitting, Δ_J, are better reproduced than previous works, with only 10-20 % over estimations,
  - experimental observation of $\Delta_{ud} > \Delta_s$ is reproduced,
  - hyperfine splittings are only 60-65 % reproduced,
  - decay constant calculation on going, f_D within experimental error and f_{D_s} encouraging.
- $\Delta_{J=0}$ and $\Delta_{J=1}$ are degenerate for $m_{\text{heavy}} > 0.2$-0.3,
- $\Delta_{J=0}$ increases as m_{heavy} decreases further, while
- $\Delta_{J=1}$ seems not to increase so much (supported by $K_1(1270) - K^*(892)$),

Future:

- finalize the analyses (all the numbers above are yet preliminary),
- would be interesting to check the Goldberger-Treiman relation, $g_\pi = \Delta / f_\pi$.
  - perhaps requires a better, relativistic scheme than this brute-force approach.

Electromagnetic Properties of Hadrons with Two Flavor Dynamical Domain Wall Fermions

Thomas Blum

Electromagnetic properties of hadrons with two flavor dynamical domain wall fermions

T. Blum (RBRC and Univ. of Connecticut),

in collaboration with

Norikazu Yamada (KEK) M. Hayakawa (RIKEN),
T. Izubuchi (Kanazawa, RBRC),

for RBC Collaboration

Introduction

EM properties of hadrons offer rich source of interesting/ important phenomena.

- Mass splitting: $\pi^+ - \pi^0 \sim +5$ MeV, $K^+ - K^0 \sim -4$ MeV, $\rho^+ - \rho^0 \sim 0$ MeV, $p - n \sim -1$ MeV, $\cdots$
- $\Gamma_{\rho^+} - \Gamma_{\rho^0}$: $\Gamma(\tau \to$ hadrons$) \to \sigma(e^+e^- \to$ hadrons$)$ in $g-2$
- light by light in $g-2$

EM splittings = $m_d - m_u$ + QED

Introducing QED to Lattice $\Rightarrow$ $m_d - m_u$

Previous work: A. Duncan, E. Eichten, H. Thacker, PRL76(1996)3894 in quenched approximation

QCD configurations

RBC, hep-lat/0411006

Use Two-flavor dynamical domain wall QCD by RBC

β_{QCD}, gauge action	0.8, DBW2
$1/a$	$1.691(53)$ GeV from m_ρ=770 MeV
	$1.688(21)(^{+69}_{-04})$ GeV from r_0=0.5 fm
Lattice size	$V = 16^3 \times 32$, L_s=12 $\Leftrightarrow V \sim$ (2 fm)^3
domain-wall height	M_5=1.8
Sea quark masses	$0.02, 0.03, 0.04 \;\Leftrightarrow\; \frac{1}{2}m_s, \frac{3}{4}m_s, m_s$
# of trajectories	5,000+ for each sea quark
	(Measurement every 20–30 trajectories)

$$U_{\mathrm{qcd}_{n,\mu}}$$

Quenched non-compact QED

$$S_{\rm em} = \sum_n \frac{1}{4e^2}(\partial_\mu A_{{\rm em},n,\nu} - \partial_\nu A_{{\rm em}n,\mu})^2,$$

$$(\ \partial_\mu f_n = f_{n+\hat{\mu}} - f_n\ )$$

Invariant under $A_{{\rm em},n,\mu} \to A_{{\rm em},n,\mu} + \partial_\mu \Lambda_n$.

Advantages:

- No auto-correlation even for arbitrarily small coupling
- No photon self-coupling $\to$ free theory: the coupling does not run.

Generation of quenched QED :

i. Generate $\tilde{A}_{{\rm em},p,\mu}$ in mom. space
with a constraint of Coulomb gauge : $\sum_{j=1}^{3} \partial_j^* A_{{\rm em},n,j} = 0$

ii. Fourier transformation to obtain $A_{{\rm em},n,\mu}$ in coordinate space

$$\Downarrow$$

$$U_{{\rm em}n,\mu} = e^{ieA_{{\rm em},n,\mu}}$$

Combining QED to QCD

QCD $\rightarrow$ QCD+QED theory,

in continuum, $\not{D} = \not{\partial} + ig\not{A}_{\rm qcd} + iQ_q e\not{A}_{\rm em}$

$\Downarrow$

on the lattice, $\mathbf{U}_{\rm qcd\times em} = U_{\rm qcd} \times (U_{\rm em})^{Q_q}$

Use $\mathbf{U}_{\rm qcd\times em}$ to solve valence quark propagators

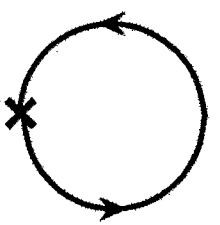
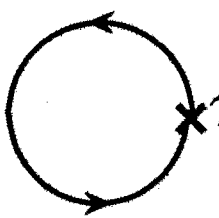
- $\mathbf{U}_{\rm qcd\times em}$ depends on Q_q, *e.g.* $Q_u = 2/3$, $Q_d = -1/3$.
  $\rightarrow$ up and down quark propagators are treated separately.
- e dependence can be searched by changing Q_q.
  $e = \sqrt{4\pi/137}$, 1.0 are examined.
- one QED configuration per a QCD configuration

Comments on π^0

QED breaks Isospin symmetry.

- π^0-singlet mixing:
  The effects start from $O(\alpha_{\rm em}^2)$. $\rightarrow$ ignored

- Disconnected diagram:
  $\langle\, P^3(t)\, P^3(0)\,\rangle$ and $\langle\, A_4^3(t)\, A_4^3(0)\,\rangle$ receive a contribution from

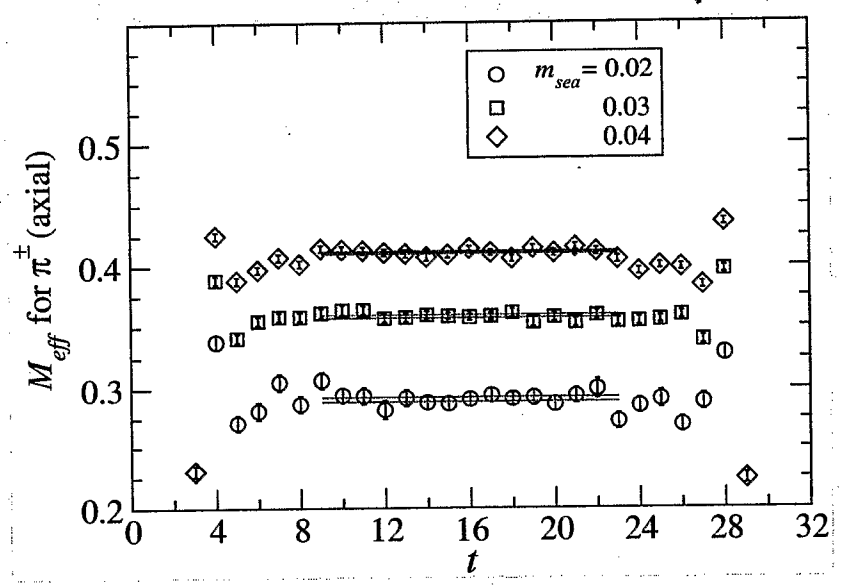
$\langle\, 0 \mid \tau^3$   $\tau^3 \mid 0\,\rangle$

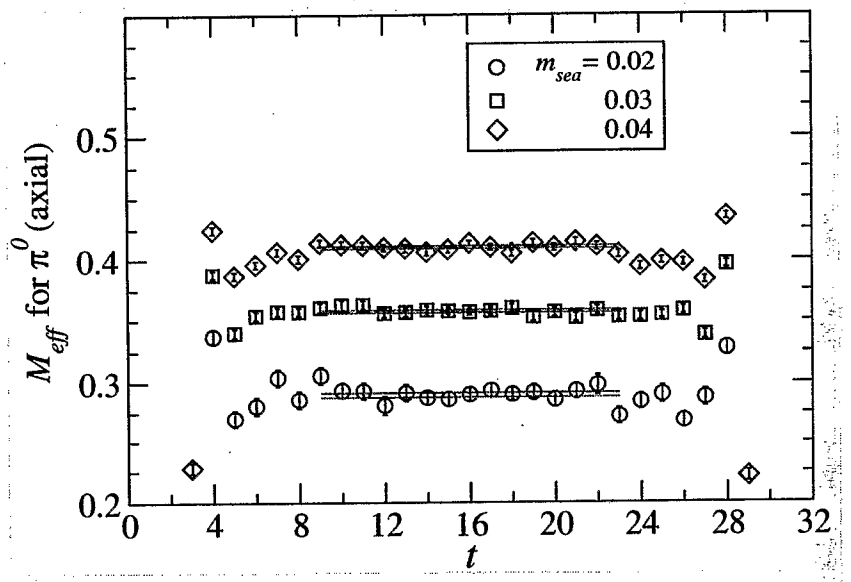
How large does this contribute to m_{π^0}? $O(\alpha_{\rm em})$ or $O(\alpha_{\rm em}^2)$?

While we can estimate the disconnected diagram explicitly, we are ignoring it at the present.

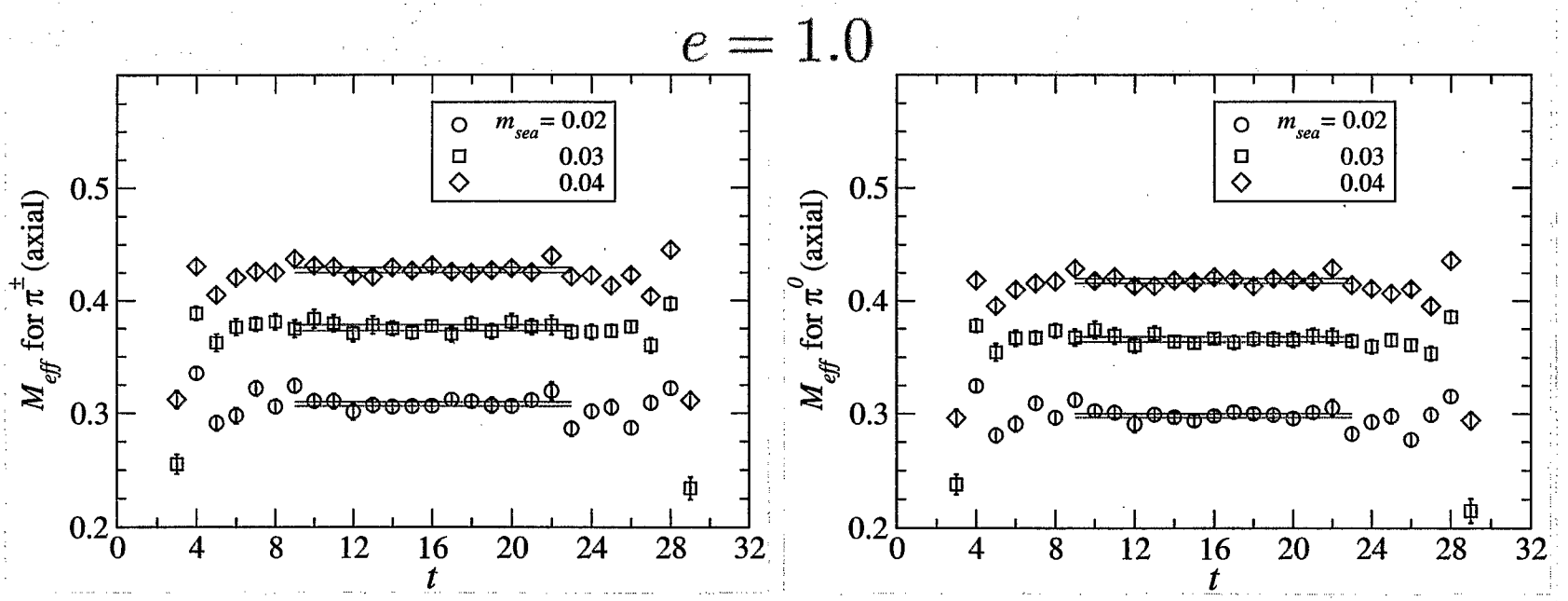
Effective mass plots

$$e = \sqrt{4\pi/137} \sim 0.3$$





Effective mass plots



Symmetry

In pure QCD, $SU(2)_L \times SU(2)_R \to SU(2)_V$ ➡ 3 NG bosons $\to \pi^{\pm,0}$

In continuum (QCD + QED) case,

$$\partial_\mu \mathcal{A}^a_\mu(x) = 2mP^a(x) + i\,\bar{q}(x)\,[\,\tfrac{\tau^a}{2}, Q\,]\,e\not{A}_{\rm em}(x)\,\gamma_5\,q(x),$$

where $\mathcal{A}^a_\mu(x)$: axial-vector current, $Q = \frac{1}{3}\begin{pmatrix} 2 & 0 \\ 0 & -1 \end{pmatrix} = \frac{1}{6}1_2 + \frac{1}{2}\tau^3.$

When $m = 0$, only $\mathcal{A}^3_\mu$ conserves.

⬇

- $U(1)_{3,L} \times U(1)_{3,R} \to U(1)_{3,V} \Rightarrow$ 1 NG boson $\to \pi^0$
- Others are massive even in $m = 0$ (*e.g* $m^2_{\pi^\pm} \sim \alpha_{\rm em} m^2_\rho$).

Chiral extrapolation

ChPT $\Rightarrow$ functional form in chiral extrapolation

We have data only at three dynamical points ($m_{\rm valence} = m_{\rm sea}$).

We fit data to linear functions of quark mass,

$$\text{Charged:} \quad m_{\pi^+}^2 = \alpha_{\rm em}\Delta_+^{(0)} + 2\left(B_0 + \alpha_{\rm em}\Delta_+^{(m)}\right)(m_f + m_{\rm res})$$

$$\text{Neutral (NG boson):} \quad m_{\pi^0}^2 = 2\left(B_0 + \alpha_{\rm em}\Delta_0^{(m)}\right)(m_f + m_{\rm res})$$

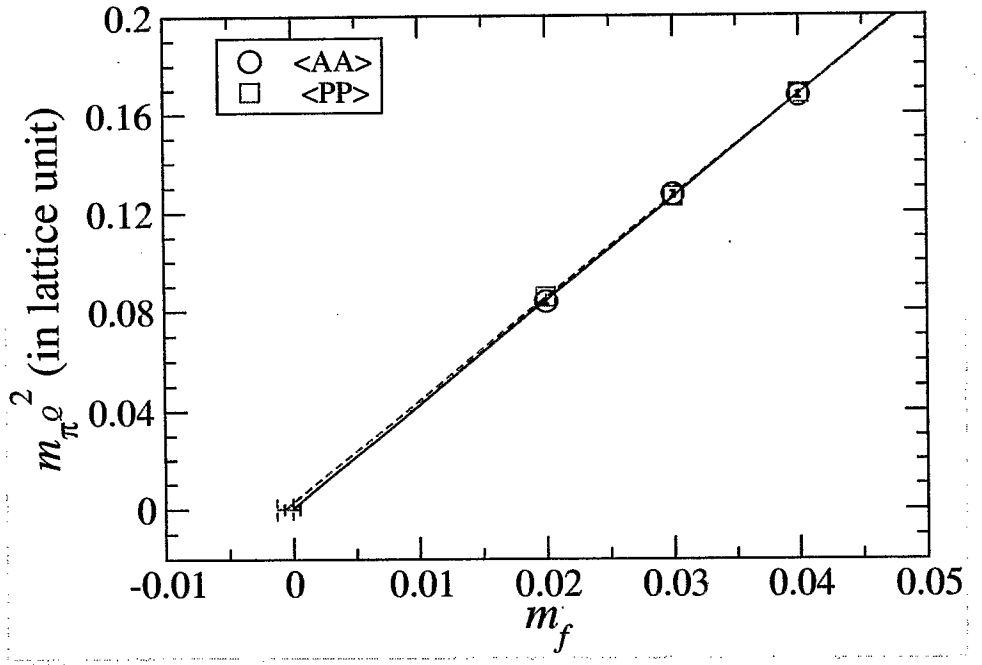
Determine B_0, $\Delta_+^{(0)}$, $\Delta_+^{(m)}$, $\Delta_0^{(m)}$ and $m_{\rm res}$.

First $m_{\rm res}$ from $m_{\pi^0}^2$ is shown.

B_0

Use π^Q (pion in pure QCD), $m^2_{\pi^Q} = 2\,B_0\,(m_f + m^{\rm qcd}_{\rm res})$

$e = 0.0$ (pure QCD)

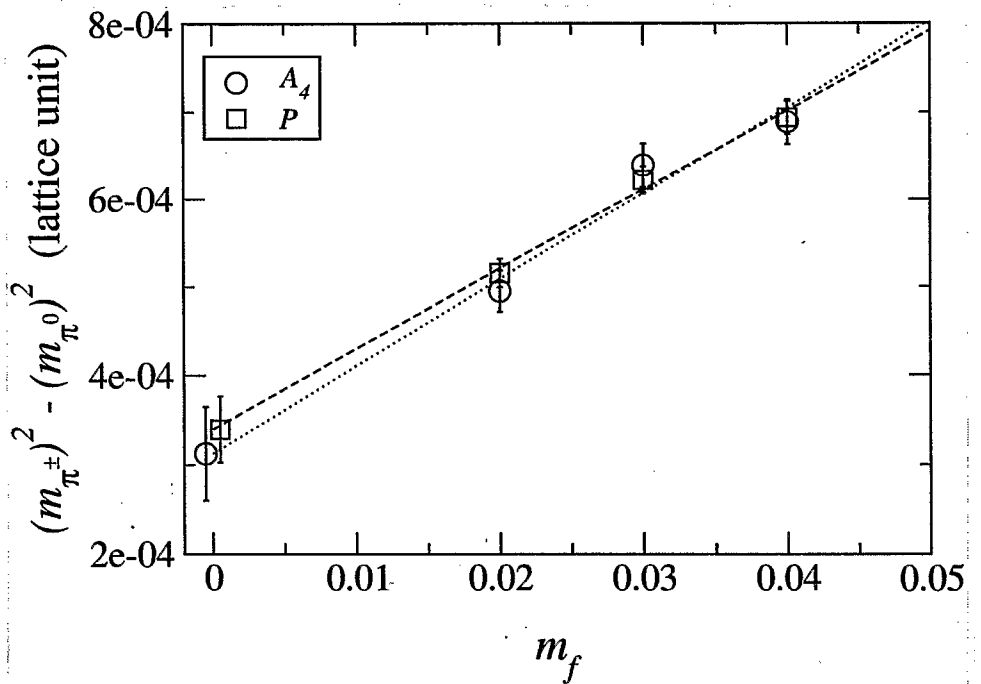


Slope ➡ B_0

$\Delta_+^{(m)} + \Delta_0^{(m)}$ and $\Delta_+^{(0)}$

$$m_{\pi^+}^2 - m_{\pi^0}^2 = \alpha_{\rm em}\left(\Delta_+^{(0)} + 2(\Delta_+^{(m)} + \Delta_0^{(m)})(m_f + m_{\rm res})\right)$$

$$e = \sqrt{4\pi/137}$$

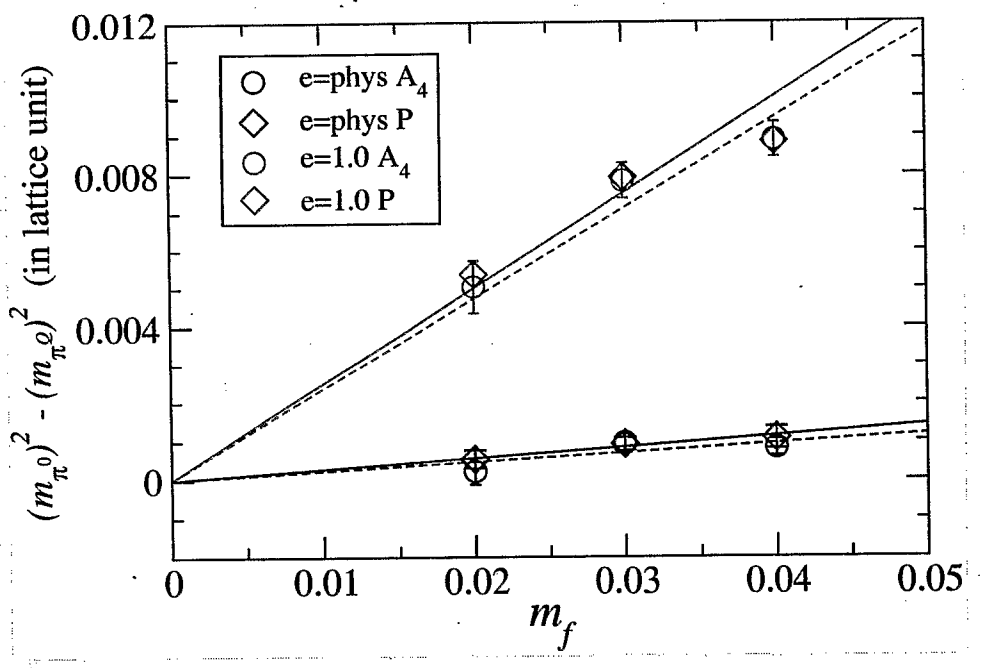


Slope ➡ $\Delta_+^{(m)} + \Delta_0^{(m)}$, Intersection ➡ $\Delta_+^{(0)}$

$\Delta_0^{(m)}$

$$m_{\pi^0}^2 - m_{\pi^Q}^2 = 2\,\alpha_{\rm em}\,\Delta_0^{(m)}\,(m_f + m_{\rm res})$$

$e = \sqrt{4\pi/137}$, and 1.0



Slope ➡ $\Delta_0^{(m)}$

Summary of bare low energy constants

We obtain

$$< AA >: B_0 = 2.09(4),\ \ \Delta_+^{(0)} = 0.0429(71),\ \ \Delta_+^{(m)} = 2.28(31),\ \ \Delta_{\pi^0}^{(m)} = 1.60(28),$$
$$< PP >: B_0 = 2.06(4),\ \ \Delta_+^{(0)} = 0.0466(51),\ \ \Delta_+^{(m)} = 2.56(29),\ \ \Delta_{\pi^0}^{(m)} = 1.94(27)$$

in lattice unit.

With above results, quark masses determination are examined.
Since we are unable to pursue non-degenerate effects, we simply assume the same LEC for Kaons:

$$\begin{aligned} m_{K^+}^2 &= \alpha_{\rm em}\Delta_+^{(0)} + (B_0 + \alpha_{\rm em}\Delta_+^{(m)})(m_{f,1} + m_{\rm res,1} + m_{f,2} + m_{\rm res,2}) \\ m_{K^0}^2 &= (B_0 + \alpha_{\rm em}\Delta_0^{(m)})(m_{f,1} + m_{\rm res,1} + m_{f,2} + m_{\rm res,2}) \end{aligned}$$

Systematic errors

- Absence of disconnected diagrams
- Finite volume effects
  Model estimates suggest about 10 % increace for $\Delta_+^{(0)}$. How about others?
- Scaling violation
- Quenched QED and dynamical strange quark

Summary

Conclusion:

- Determinations of quark masses by EM splitting are examined in dynamical DW QCD+QED.
-

Future:

- Mesons consisting of non-degenerate quarks$\Rightarrow$ more realistic determination
- Study of systematic errors
- Vector mesons and baryons (Doi's Talk) in progress.

Quarkonia Correlators and Spectral Functions at T>0

Peter Petreczky

Quarkonia correlators and spectral functions at T>0

Péter Petreczky
RBRC and Physics Department

QGP formation ⇨ dissolution of different quarkonium states Matsui and Satz '86

$c\bar{c}$	$\psi'(2S)$	$\chi_c(1P)$	$J/\psi(1S)$	
$b\bar{b}$		$\Upsilon''(3S)$, $\chi_b'(2P)$	$\chi_b(1P)$	$\Upsilon(1S)$
$\langle r^2\rangle^{1/2}$ fm	0.9	0.7	0.4	0.2

temperature

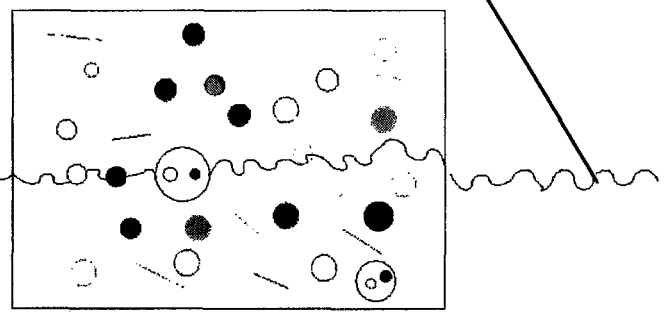
Lattice correlator → $G(\tau,T)=\int_0^\infty d\omega\sigma(\omega,T)\frac{\cosh(\omega(\tau-1/(2T))}{\sinh(\omega/(2T))}$ e.g. γ^*, dilepton rate

⇩

MEM

⇩

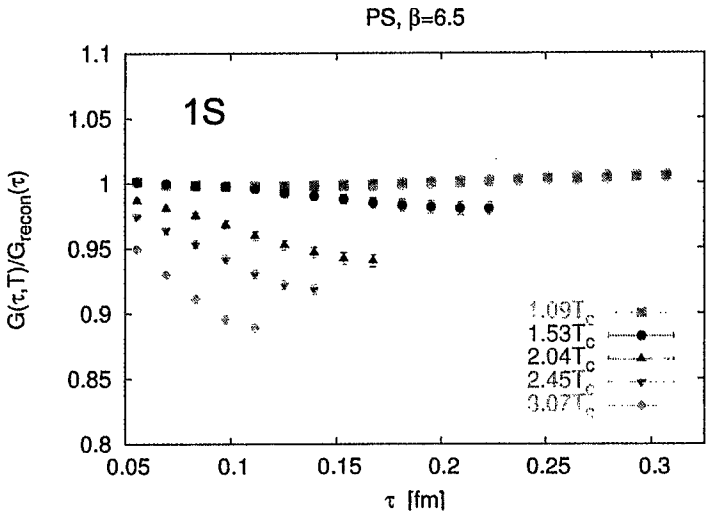
spectral functions : coupling of the medium with external probe

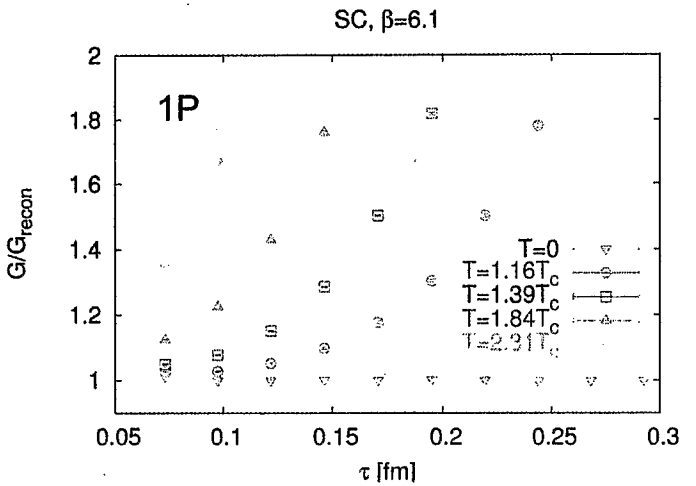


Charmonia and bottomonia spectral functions from lattice,
A. Jakovác, P.P., K. Petrov, A. Velytsky, hep-lat/0509138, work in progress

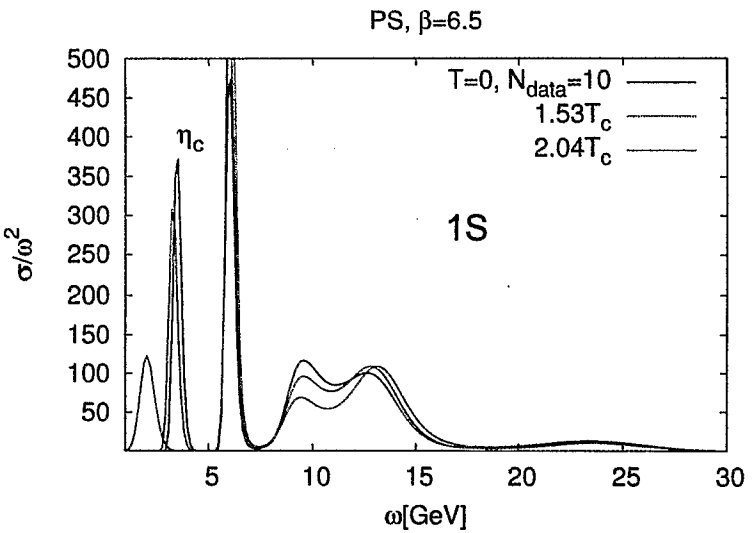
→ Transport of heavy quarks in QGP, P.P. and D. Teaney, hep-ph/0507318

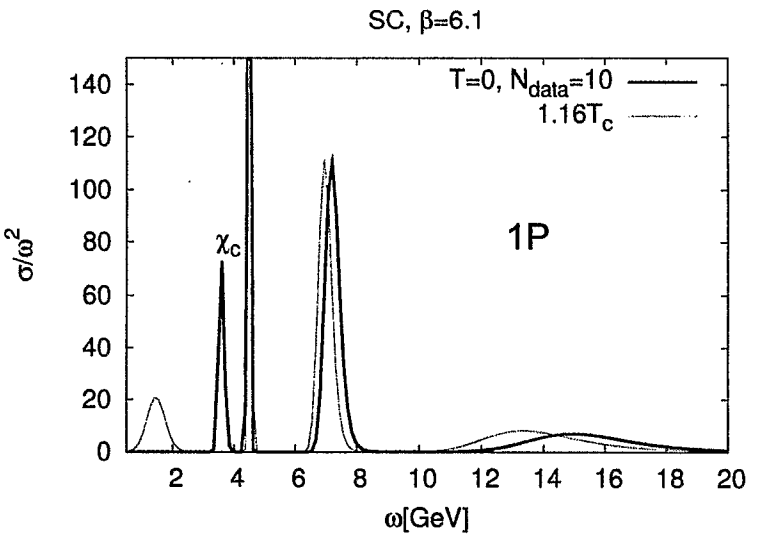
Charmonia correlators and spectral functions





no change in $\sigma(\omega, T)$ ⇨ $G(\tau,T)/G(\tau,T=0)=1$





in agreement with Datta, Karsch, P.P., Wetzorke, PRD 69 (04) 094507

Bottomonia correlators and spectral functions

$$\xi = a_s/a_t = 4,\ a_t^{-1} = 10.9\ \text{GeV},\ N_t = 16 - 36$$

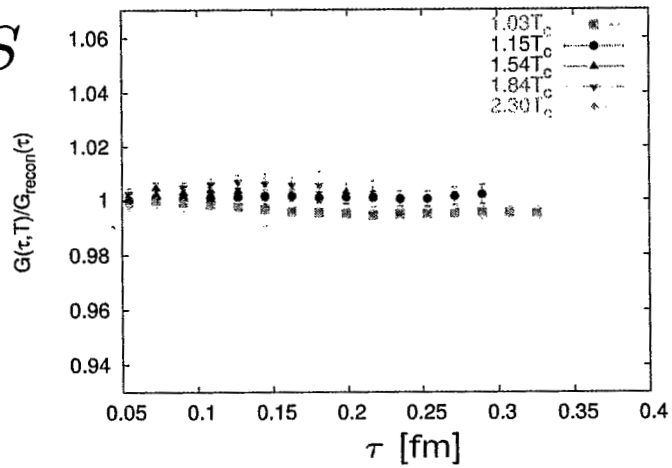
1S states are dissolved only at $T > 3T_c$

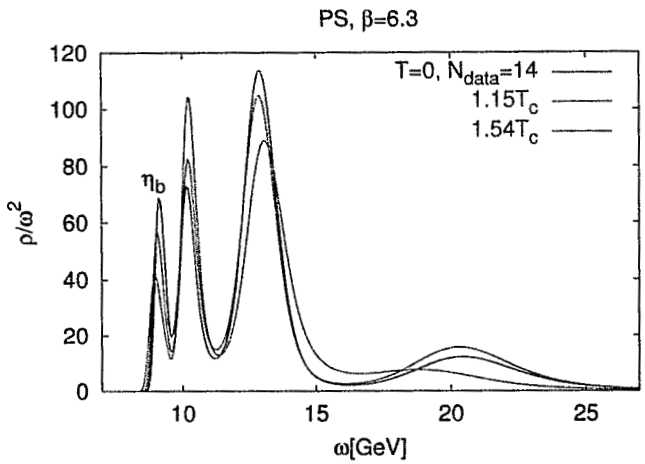
1P states are dissolved at $T \sim 1.15T_c$

expected χ_b survive till $\sim 1.5T_c$

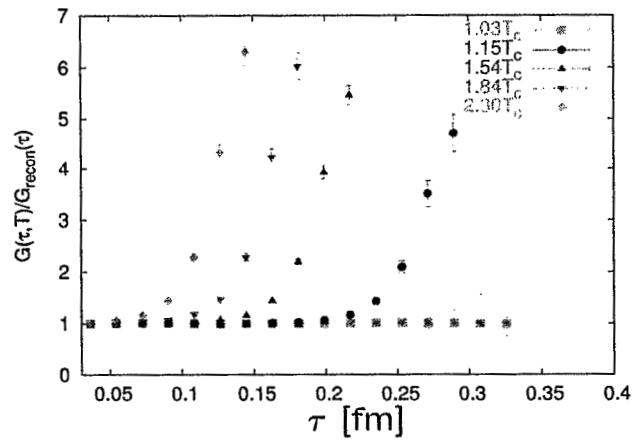
A. Jakovác, P.P., K. Petrov, A. Velytsky, hep-lat/0509138

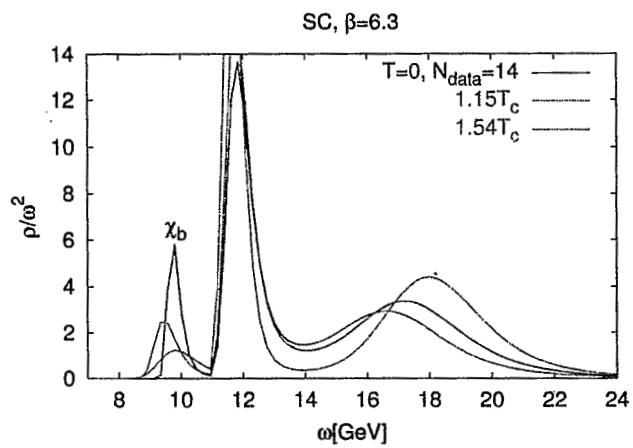
$1S$





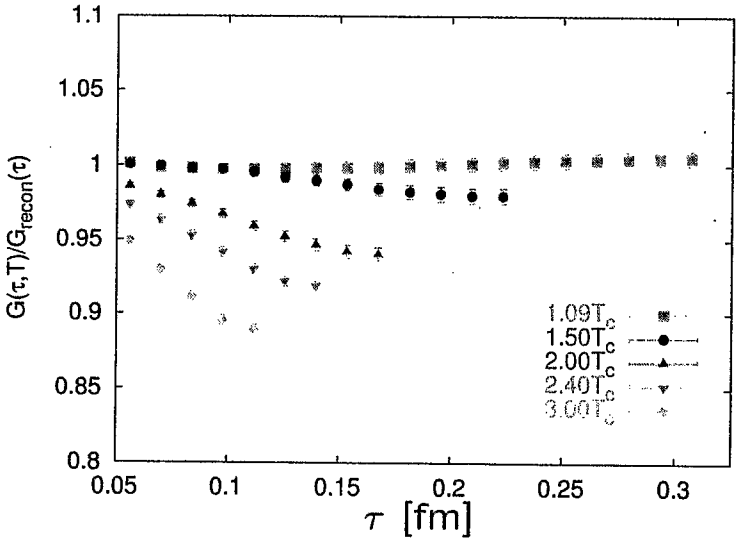
$1P$





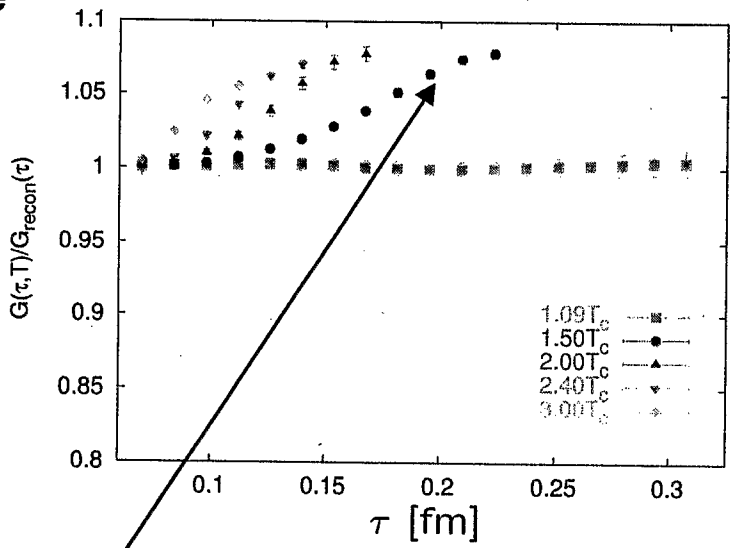
Vector correlator and heavy quark diffusion

Pseudo-scalar (η_c)



1S charmonium states survive

Vector (J/ψ)



Vector current is conserved $\longrightarrow$ fluctuations of charm number

$$\sigma_V^{ii}(\omega) = F_{J/\psi}^2(T)\delta(\omega^2 - m_{J/\psi}^2(T)) + \frac{1}{4\pi^2}\omega^2\sqrt{1-\frac{4m_D^2(T)}{\omega^2}} + \chi_s(T)\left(\frac{T}{M}\right)\omega\delta(\omega)$$

$$\frac{1}{3}\chi_s(T)\frac{T}{M}\omega\cdot\frac{1}{\pi}\cdot\frac{\eta}{\omega^2+\eta^2}$$

Interactions

Free streaming :Collision less Botzmann equation

Effective Langevin theory

$$\eta = \frac{T}{M}\frac{1}{D} \qquad \partial_t N_c + D\nabla^2 N_c = 0$$

P.P. and D. Teaney, hep-ph/0507318

RHIC : large transport of heavy quarks

$D \simeq 1/(2\pi T)$ $\Rightarrow$ should be seen in the lattice correlator

Spin 3/2 Pentaquark from Lattice QCD
Isospin Breaking of Baryon Masses from Lattice QCD

Takumi Doi

Spin 3/2 pentaquark from lattice QCD

Isospin breaking of baryon masses from lattice QCD

Takumi Doi (RBRC)

(1) In collaboration with

N.Ishii[1], Y.Nemoto[2], M.Oka[1], H.Suganuma[3]

[1](Tokyo Inst. of Tech.) [2](Nagoya U.) [3](Kyoto U.)

(2) In collaboration with

T.Blum[1,2], M.Hayakawa[3],T.Izubuchi[2,4], N.Yamada[5]

[1](Univ. of Connecticut) [2](RBRC) [3](RIKEN) [4](Kanazawa U.) [5](KEK)

Introduction(pentaquark study)

- The "discovery" of Θ^+ (1540) baryon by LEPS(2003) heralds a new era of exotics in QCD.
  - **B=+1, S=+1➔ manifestly exotic (*uudd$\bar{s}$*)**
  - Other exotics ? (Tetra, Nona …)
- The controversial status for Θ^+
  - 10 positive results vs. many null results (high-energy, CLAS)
- Lattice QCD is another powerful "experiment".
  - Confirm/exclude the existence of Θ^+
  - What is the possible spin/parity ?

Possibility of higher spin state

- $J^P=1/2^-$ **(NK s-wave)** vs. $1/2^+$ (NK p-wave)
  - **Lattice, Sum rule**
  - **Difficult to explain the width** $\Gamma < 1 - 10\text{MeV}$
- If $J^P=3/2^-$
  - **Decay to NK is suppressed by D-wave**

    c.f. $N+K^* = 1.83\text{GeV}$, $K+\Delta = 1.73\text{GeV}$ $(I\neq 0)$
    - Large centrifugal barrier → narrow width
- If $J^P=3/2^+$
  - **LS-partner of JW model**
  - **Decay to NK is p-wave**

Y.Kanada-En'yo et al. hep-ph/0404144
R.L.Jaffe et al. hep-ph/0408046
T.Shinozaki et al. hep-ph/0409103

The difficulty in Lattice QCD

- **Difficult to separate Θ^+ from two particle scattering state**

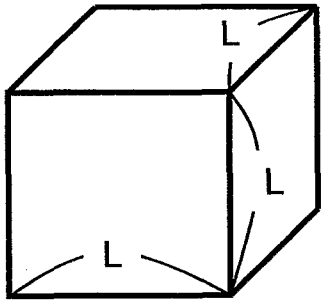
  - **It is difficult to extract excited state signal besides ground state signal**

$$\Pi(t) = \sum_{\vec{x}} \langle \eta(x)\eta(0)\rangle = \sum \lambda_i^2 \exp(-E_i t)$$
$$\xrightarrow[t\to\infty]{} \lambda_g^2 \exp(-E_g t)$$

→ NK state will dominate

Θ^+ (exp):	**1540MeV**
N+K:	**1440MeV**
N+K*:	**1800MeV**

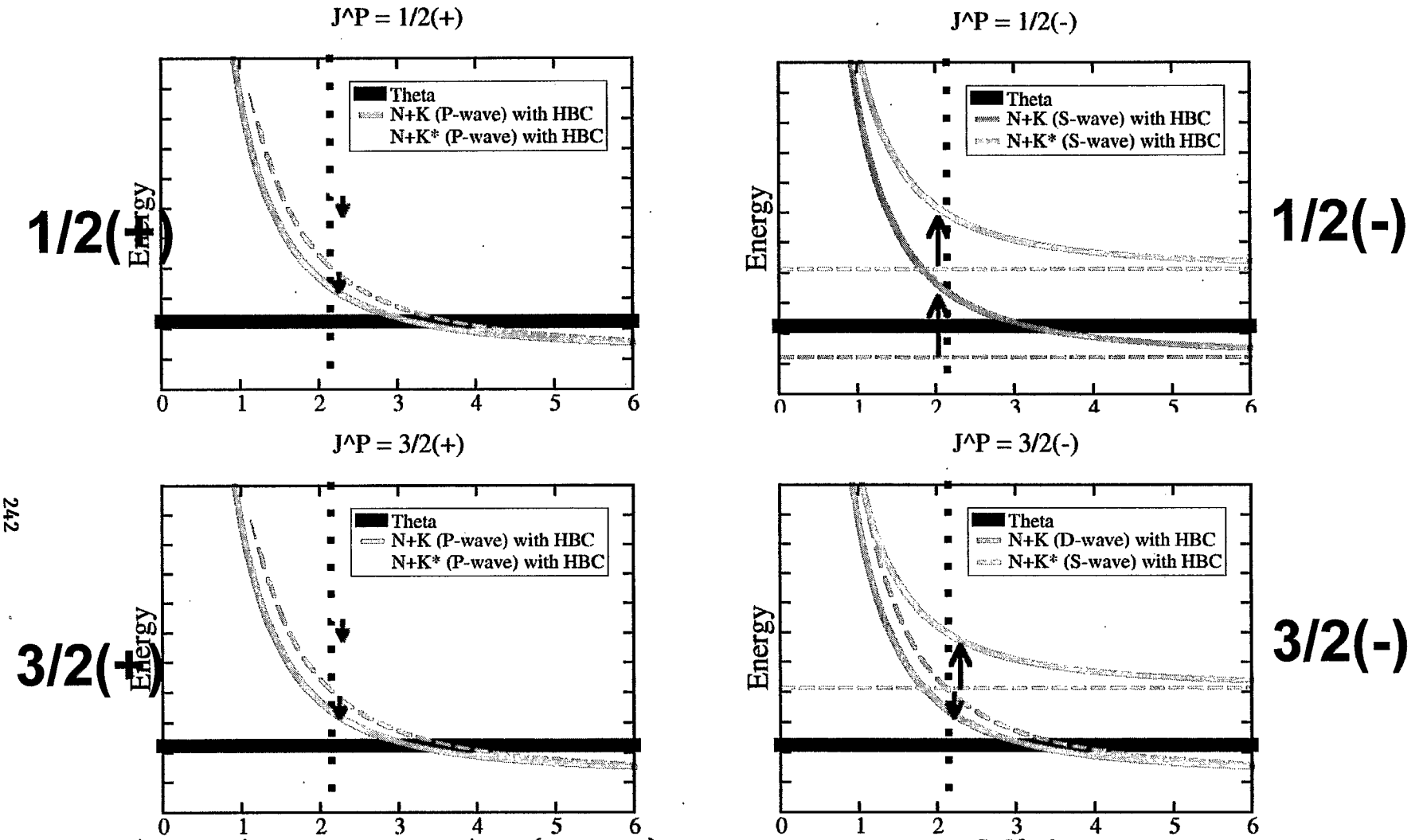
Volume dependence and Hybrid Boundary Condition (HBC)



- **Momenta are discretized !**
  - Periodic BC (PBC) ➔ $p_i = 2n_i\pi/L$
  - Anti-periodic BC (APBC) ➔ $p_i = (2n_i+1)\pi/L$

	PBC	HBC
u-quark	PBC	APBC
d-quark	PBC	APBC
s-quark	PBC	PBC
N (uud,udd)	PBC→ $\vec{p}_{min} = \vec{0}$	APBC→ $\vec{p}_{min} = \pi\vec{n}/L$
K,K* ($u\bar{s}$,$d\bar{s}$)	PBC→ $\vec{p}_{min} = \vec{0}$	APBC→ $\vec{p}_{min} = \pi\vec{n}/L$
Θ^+ ($uudd\bar{s}$)	PBC→ $\vec{p}_{min} = \vec{0}$	PBC → $\vec{p}_{min} = \vec{0}$

$$E_{\min}(NK) \simeq \sqrt{m_N^2 + p_{\min}^2} + \sqrt{m_K^2 + p_{\min}^2}$$



$|\vec{p}_{min}| = 2\pi/L$ (PBC)

$\rightarrow \sqrt{3}\pi/L$ (HBC)

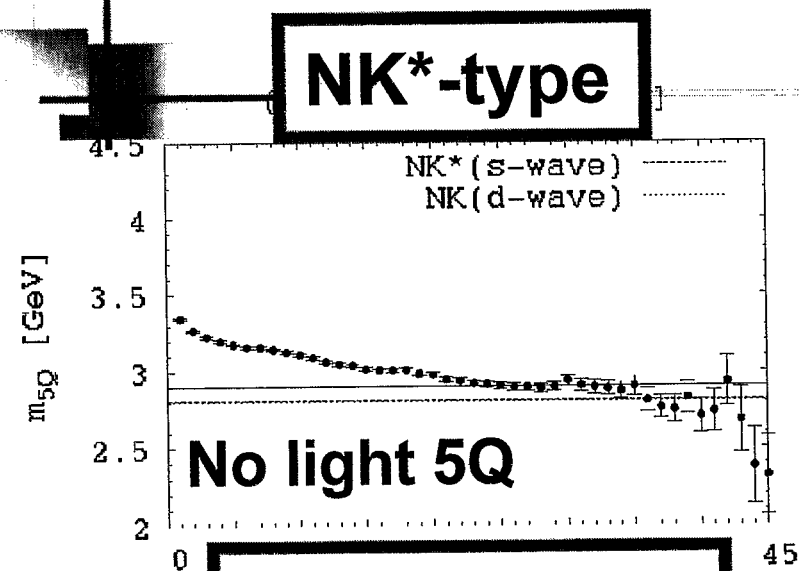
(P/D-wave)

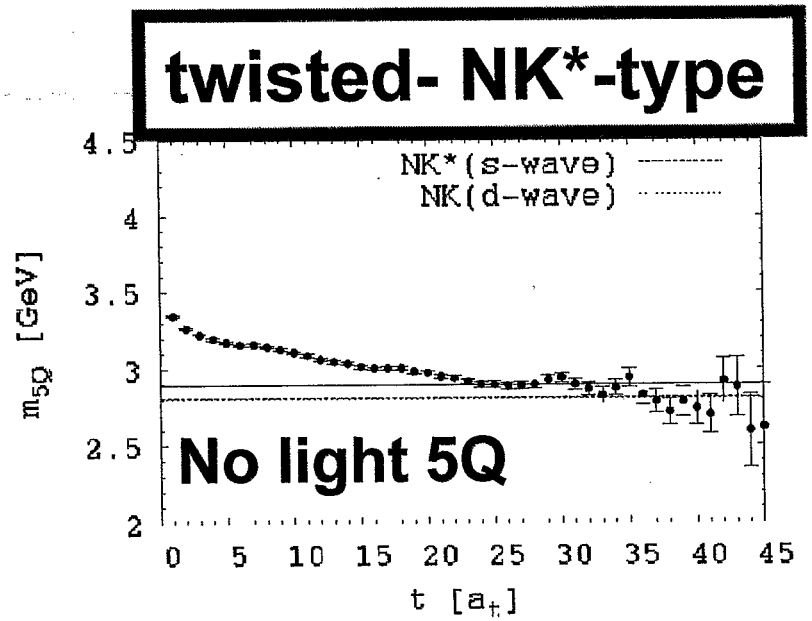
$|\vec{p}_{min}| = 0$ (PBC)

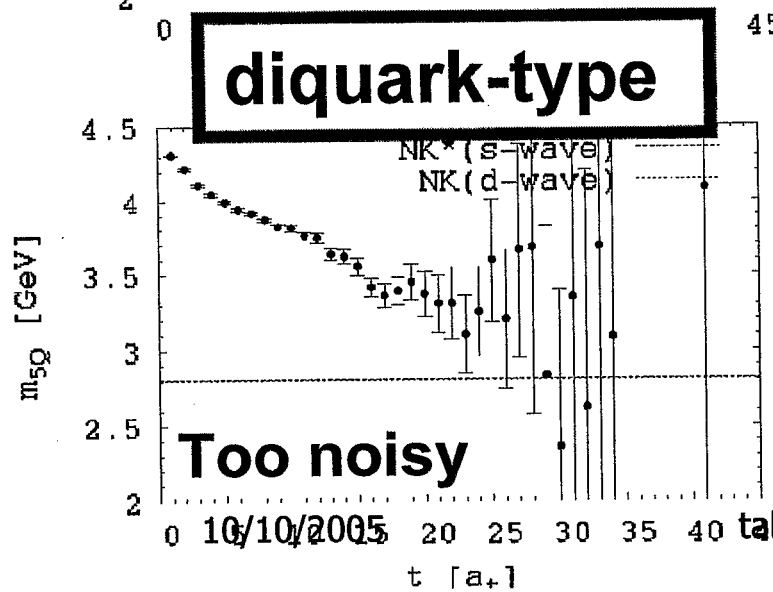
$\rightarrow \sqrt{3}\pi/L$ (HBC)

(S-wave)

Effective mass for $J^P=3/2(-)$







NK*–type

$$\eta_\mu = \epsilon^{abc}\{u_a^T C\gamma_5 d_b\}u_c \cdot (\bar{s}_d\gamma_\mu d_d) + (u \leftrightarrow d)$$

twisted NK*–type

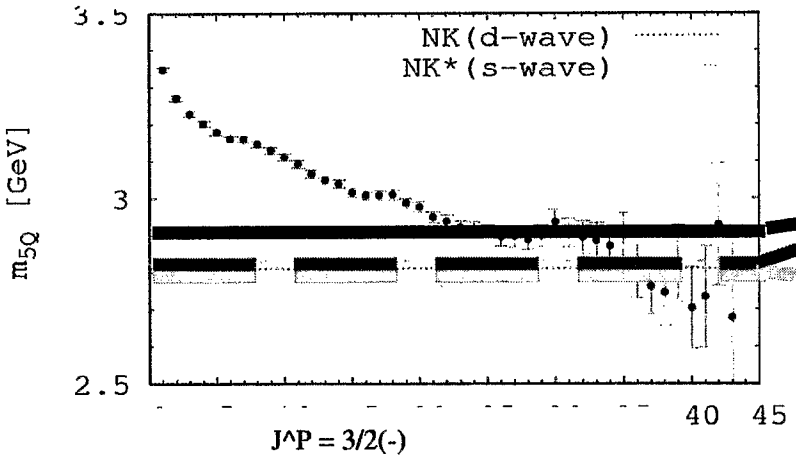
$$\eta_\mu = \epsilon^{abc}\{u_a^T C\gamma_5 d_b\}u_d \cdot (\bar{s}_d\gamma_\mu d_c) + (u \leftrightarrow d)$$

diquark–type

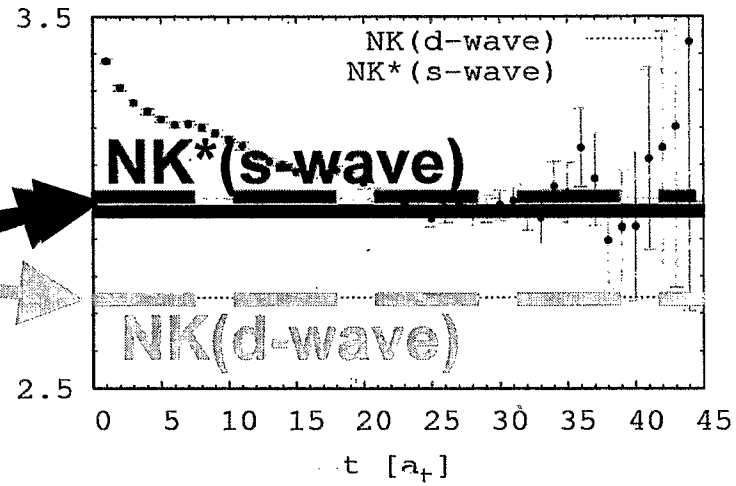
$$\eta_\mu = \epsilon^{abc}\epsilon^{def}\epsilon^{cfg}\{u_a^T C\gamma_5 d_b\}\{u_d^T C\gamma_5\gamma_\mu d_e\}C\bar{s}_g^T$$

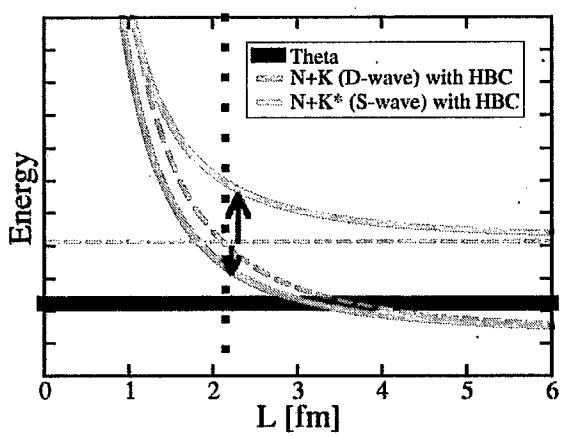
HBC analysis for $J^P=3/2(-)$ (NK*-type op.)

Standard(Periodic) BC



Hybrid BC (HBC)

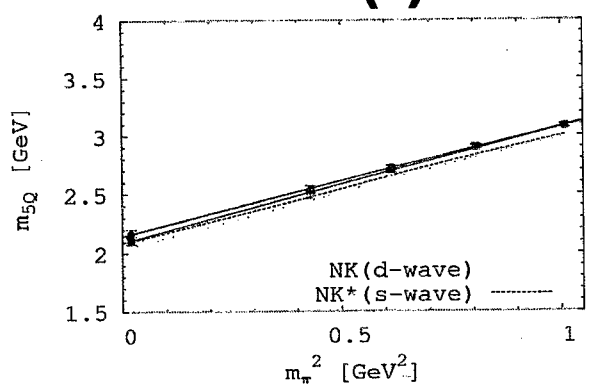




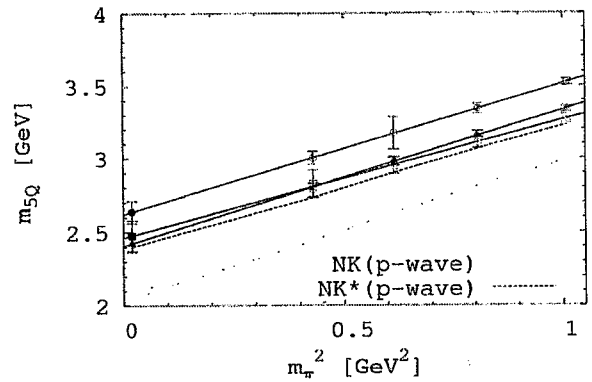
Considering the energy shift of PBC→ HBC, the plateau is NK*(s-wave) scatt. state.

Chiral extrapolation (J^P=3/2(-/+))

3/2(-)



3/2(+)



	3/2(-)	3/2(+)
NK*-type:	**M(5Q)=2.17(4)GeV**	**M(5Q)=2.64(7)GeV**
twisted NK*-type:	**M(5Q)=2.11(4)GeV**	**M(5Q)=2.48(10)GeV**
diquark-type:	**-----**	**M(5Q)=2.42(6)GeV**

We find no light low-lying 5Q state for both of J^P=3/2(-/+)

245

Isospin breaking of baryon masses from lattice QCD

Takumi Doi (RBRC)

(2) In collaboration with

T.Blum[1,2], M.Hayakawa[3], T.Izubuchi[2,4], N.Yamada[5]

[1](Univ. of Connecticut) [2](RBRC) [3](RIKEN) [4](Kanazawa U.) [5](KEK)

Motivation

- Isospin breaking of hadrons is related to important physics in QCD/QED.
  - Mass splitting:
    - $\pi^+ - \pi^- = +4.59$ MeV
    - $K^+ - K^0 = -4.00$ MeV
    - $p - n = -1.29$ MeV

    [Origin]: QED + $(m_u - m_d)$

  ➔ quark mass ➔ strong CP problem ?
  - Vacuum polarization contribution in muon g-2

One of the longstanding problem

QED: p > n
QCD: p < n
Gasser-Leutwyler(82)

Framework

- **Quenched QED + unquenched QCD**

A.Duncan, E.Eichten, H.Thacker, PRL76(1996)3894

- **QED configs:** $S_{em} = 1/4e^2 \sum (\partial_\mu A_\nu^{em} - \partial_\nu A_\mu^{em})^2$
  - quenched non-compact QED
    - Free theory, no run in coupling, no autocorrelation
- **QCD configs:**
  - Nf=2 dynamical domain-wall QCD
    - good chiral symmetry (RBC, hep-lat/0411006)
    - DBW2 gauge action, beta=0.8
    - a^{-1}=1.7GeV, V=16^3X32(x12), m_u,m_d=1/2m_s-m_s

Baryon correlation function

- Two point correlation function $\sum_{\vec{x}} \langle J_p(x) \bar{J}_p(0) \rangle$ with QCD+QED propagator

$$\bar{q}(x)[U_\mu^{QCD}(x) \times (U_\mu^{QED})^Q] q(x+\mu)$$

  - Note: in order to obtain the first order isospin breaking to the mass, it is not necessary to include the isospin breaking in the wave function.
- Charge dependence is analyzed with

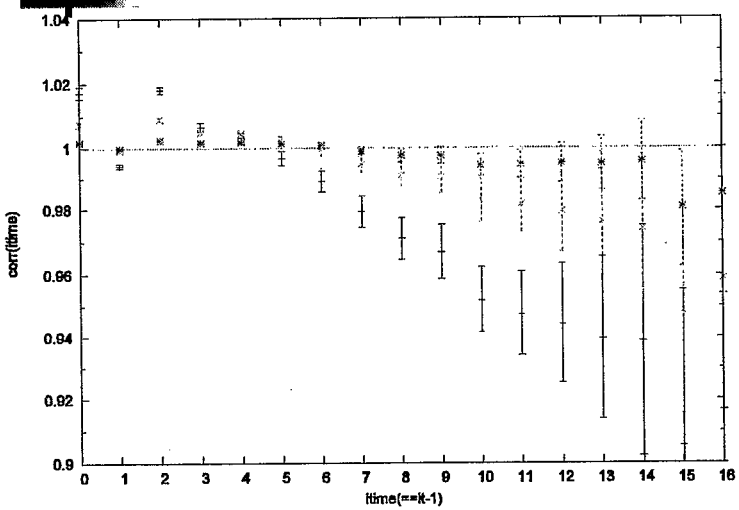
$$e = 0,\ \sqrt{4\pi/137} (= 0.3),\ (0.6),\ 1.0$$

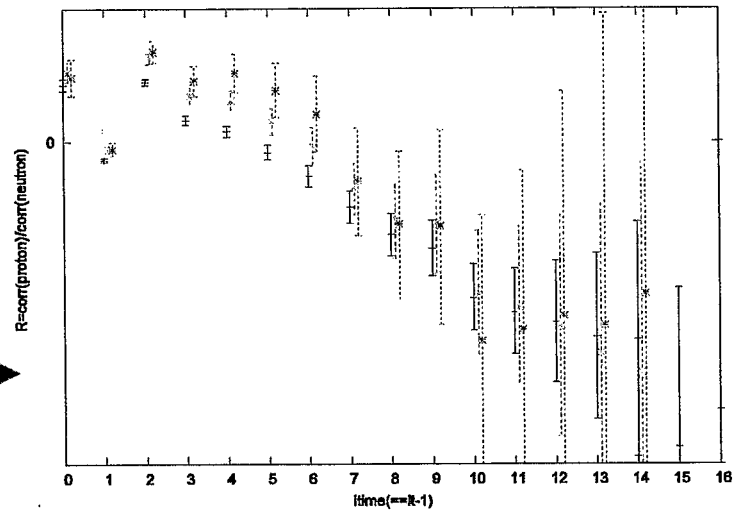
where Q_u=+2/3e, Q_d=-1/3e

Extract the mass difference

- **We focus on the mass difference directly.**
  - $\Pi(\text{proton}) = A_p \exp(-m_p t)$
  - $\Pi(\text{neutron}) = A_n \exp(-m_n t)$
- $R = \Pi(\text{proton})/\Pi(\text{neutron})$
  - $R \rightarrow (1+\delta A) + \boxed{(m_n - m_p)}\, t$, $(\delta A = (A_p - A_n)/A_n)$
- **The slope of t** is directly related to the **proton-neutron mass difference**
- Statistical fluctuation is expected to be canceled in the ratio, which **improves S/N**

Plot of Π(proton)/Π(neutron)





[rescaled to Q=physical]

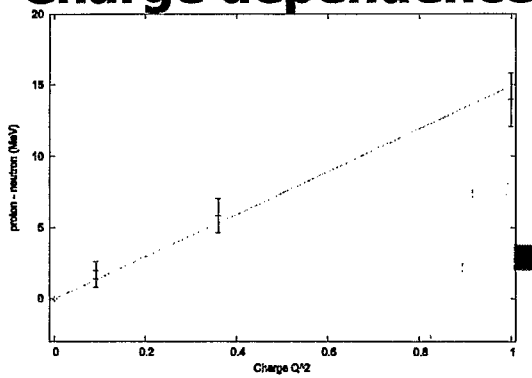
The negative slope corresponds to m(proton) > m(neutron) from the QED effect (m_u=m_d)

The results from different Q agree with each other

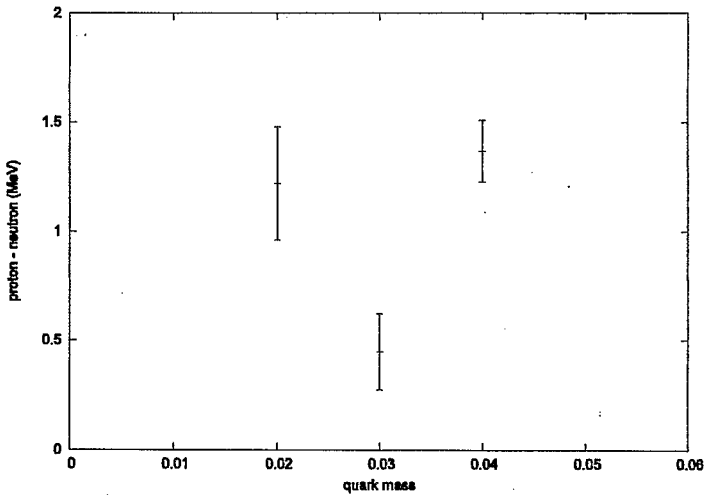
(relative error is smaller for large Q)

Proton neutron mass difference from the QED effect

Charge dependence



proton-neutron at Q=physical



The lattice result indicates proton > neutron (QED)

c.f. Cottingham formula:

M(p)-M(n)(QED)= 0.76MeV

Quark mass difference is expected to flip the inequality proton < neutron

M(p)-M(n)~0.5-1.5MeV

(very preliminary)
Finite volume artifact could be large

Summary

Pentaquark study

- We have studied Θ^+ in **J^P=3/2(+/-) channels** as well as J^P=1/2(+/-) with clover fermion on anisotropic lattice using **NK*-type, twisted NK*-type, diquark-type currents.**
- **Only massive states** have been found:
  - **J^P=3/2(-): m=2.1~2.2GeV J^P=3/2(+): m=2.4~2.6GeV**
- **HBC method** has found **no compact 5Q resonance.**
- Future: Multiquark state physics, Other exotics

Isospin breaking study

- We have studied **the QED effect** on baryon masses from quenched QED + Nf=2 dynamical domain wall QCD.
  - Focusing the isospin breaking is important to improve S/N
- **M(proton)-M(neutron)≅0.5-1.5MeV (QED)**
  - Tendency is consistent with model calc.
- M(proton)<M(neutron) from quark mass is next step
- Future: Finite volume artifact, Other octet/decuplet, etc.

DI = 3/2 Kaon Weak Matrix Elements with Non-zero Total Momentum

Takeshi Yamazaki

$\Delta I = 3/2$ kaon weak matrix elements with non-zero total momentum

Takeshi YAMAZAKI

for the RBC Collaboration

RIKEN BNL Research Center

the annual RBRC Scientific Review Committee Meeting

October 10 – 12 2005

Introduction

Motivation :
Understand strong interaction effect in weak decay process

$K \to \pi\pi$ weak decay process has unsolved puzzle
$\Delta I = 1/2$ selection rule

$$\frac{\mathrm{Re}A(K^0 \to (\pi\pi)_0)}{\mathrm{Re}A(K^0 \to (\pi\pi)_2)} = \frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \approx 22$$

CP violation parameter ε'/ε.

$$\frac{\varepsilon'}{\varepsilon} = \begin{cases} (20.7 \pm 2.8) \times 10^{-4} & \text{(KTeV)} \\ (15.3 \pm 2.6) \times 10^{-4} & \text{(NA48)} \end{cases}$$

Recently new method for calculation of weak matrix elements is proposed by two groups.
'05 Kim, Sachrajda and Sharpe, and Christ, Kim and Yamazaki

Purpose

To attempt generalized formula to
$\Delta I = 3/2$ $K \to \pi\pi$ decay and obtain $\mathrm{Re}A_2$

Generalized formula ($\vec{P} = (0, 0, 2\pi/L)$)

'05 Kim, Sachrajda and Sharpe, and Christ, Kim and Yamazaki

Relation of on-shell decay amplitude in infinite volume $|A|$(CM) and in finite volume $|M|$(Lab, $\vec{P} \neq 0$)

$$|A|^2 = 8\pi\gamma^2 \left(\frac{E_{\pi\pi}}{p}\right)^3 \left\{ p' \frac{\partial \delta}{\partial p'} + p' \frac{\partial \phi_{\vec{P}}}{\partial p'} \right\}_{p'=p} |M|^2$$

where

$$E_{\pi\pi}^2 = (E_{\pi\pi}^{\mathrm{Lab}})^2 - \vec{P}^2 = 4(m_\pi^2 + p^2) = m_K^2, \quad \gamma = E_{\pi\pi}^{\mathrm{Lab}} / E_{\pi\pi}$$

δ : scattering phase shift

$$\tan \phi_{\vec{P}}(q) = -\frac{\gamma q \pi^{3/2}}{Z_{00}^{\vec{P}}(1; q^2; \gamma)},$$

$$Z_{00}^{\vec{P}}(1; q^2; \gamma) = \frac{1}{\sqrt{4\pi}} \sum_{n \in \mathbb{Z}^3} \frac{1}{n_1^2 + n_2^2 + \gamma^{-2}(n_3 + 1/2)^2 - q^2}$$

$\delta(p)$ is obtained by $\delta(p) = n\pi - \phi_{\vec{P}}(q), \; q = Lp/2\pi.$

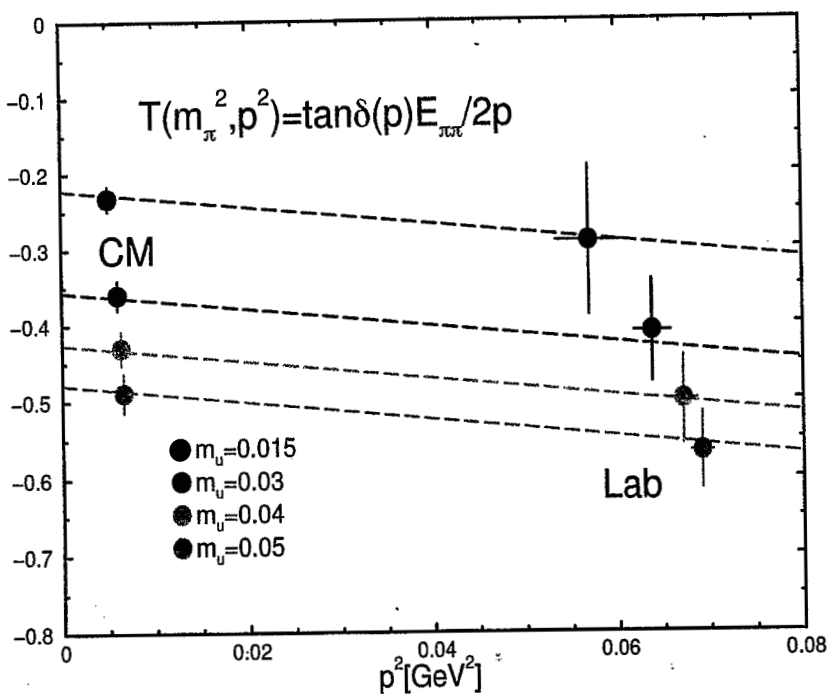
'95 Rummukainen and Gottlieb

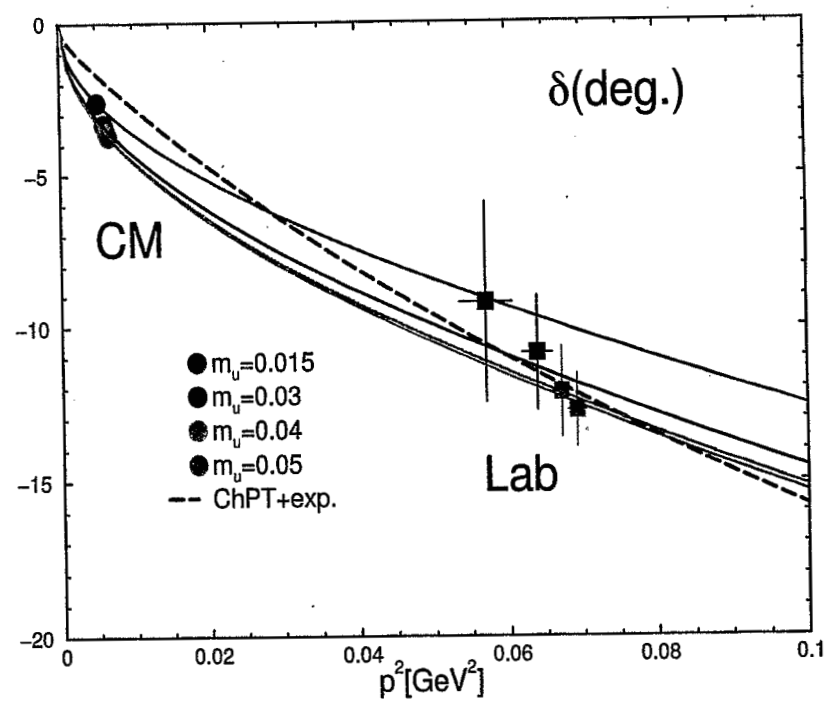
δ_l $(l > 0)$ is neglected.

$I = 2$ Scattering phase shift

To obtain $\dfrac{\partial\delta}{\partial p}$, we carry out global fitting of $T(m_\pi^2, p^2)$ for m_π^2 and p^2

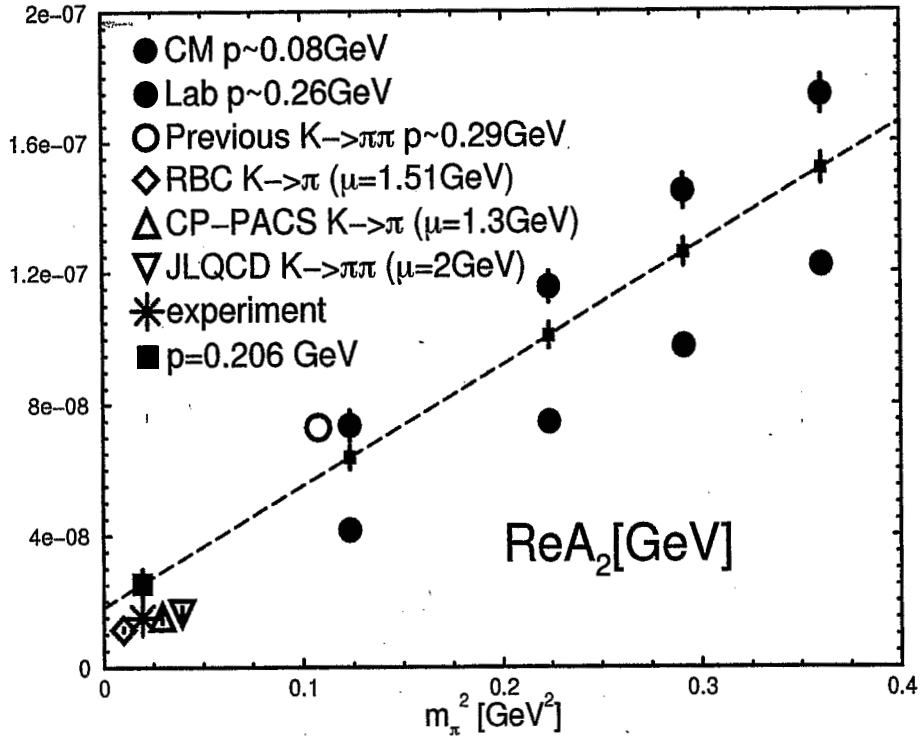
$$T(m_\pi^2, p^2) = \frac{\tan\delta(p)}{p}\frac{E_{\pi\pi}}{2} = A_{10}m_\pi^2 + A_{20}m_\pi^4 + A_{01}p^2$$





$\partial\delta/\partial p$ is extracted from fit result.(Solid lines in right figures)

Preliminary result of ReA_2[GeV] ($\mu = 1.44$[GeV])



Dashed lines are results of global fittings.

Result at physical point,

$$m_\pi = 0.140[\text{GeV}]$$
$$m_K = 0.498[\text{GeV}]$$
$$p = 0.206[\text{GeV}],$$

is presented by red square symbol.

Fitting function

$$\text{Re}A_2 = C_{00} + C_{10}m_\pi^2 + C_{01}p^2 + C_{11}m_\pi^2 p^2$$

	ReA_2[GeV]
fitting result	$2.54(43)\times10^{-8}$
experiment	$1.50 \quad \times10^{-8}$

Neutron Electric Dipole Moment from Lattice QCD Calculations

Sinya Aoki

Neutron Electric Dipole Moment from Lattice QCD Calculations

Sinya Aoki (RBRC/University of Tsukuba)
for CP-PACS collaboration

The annual RBRC Scientific Review Committee Meeting
at BNL
October 10, 2005

Introduction

θ term in QCD $$i\theta \frac{1}{32\pi^2} \int d^4x\, \epsilon^{\mu\nu\alpha\beta} F_{\mu\nu}(x) F_{\alpha\beta}(x) \equiv i\theta Q$$

CP odd, topological

➡ Neutron Electric Dipole Moment(NEDM)

Experimental bound $|\vec{d}_n \theta| \leq 6.3 \times 10^{-26} e \cdot \mathrm{cm}$

Model estimates $|\vec{d}_n| \simeq 10^{-15} \sim 10^{-17} e \cdot \mathrm{cm}$

➡ $\theta = \theta_{\mathrm{QCD}} + \theta_{\mathrm{EW}} \leq O(10^{-8})$ Strong CP problem !

However a sign of NEDM disagrees among various models !

➡ The first principle calculation of NEDM is desired.
This is a challenge of lattice QCD !

My Talk:
Feasibility study for lattice QCD Calculations of NEDM by two different methods.

NEDM from electromagnetic form factors

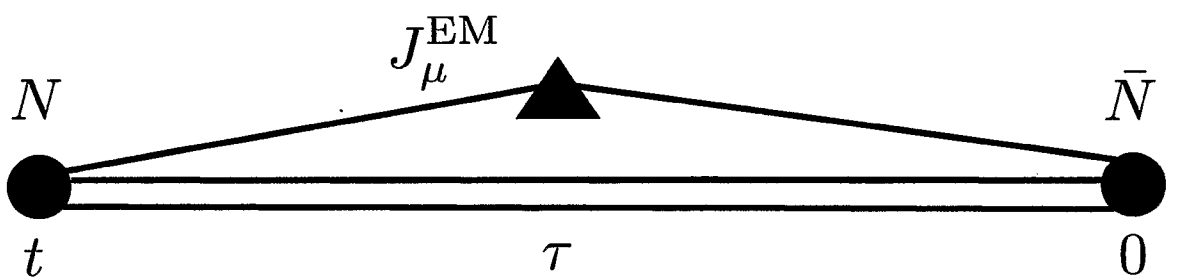
$$\langle N(p,s)|J_\mu^{\rm EM}|N(p',s')\rangle = \bar{u}(p,s)\left[\frac{F_3(q^2)}{2m_N}q_\nu\sigma_{\mu\nu}\gamma_5 + \cdots\right]u(p',s')$$

$q^2 \to 0$ CP-odd part $q = p - p'$

NEDM $$|\vec{d}_n| = \lim_{q^2\to 0}\frac{F_3(q^2)}{2m_N} = \frac{F_3(0)}{2m_N}$$

Lattice simulations

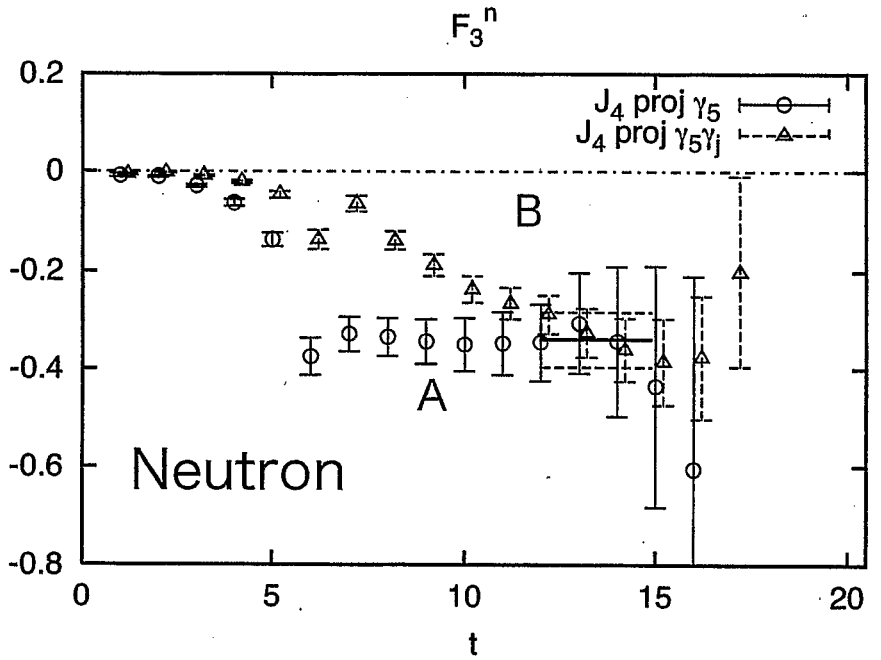
3-pt function $$G^\theta_{NJ_\mu N}(q,t,\tau) = \langle\theta|N(\vec{p},t)J_\mu^{\rm EM}(\vec{q},\tau)\bar{N}(\vec{p}',0)|\theta\rangle$$

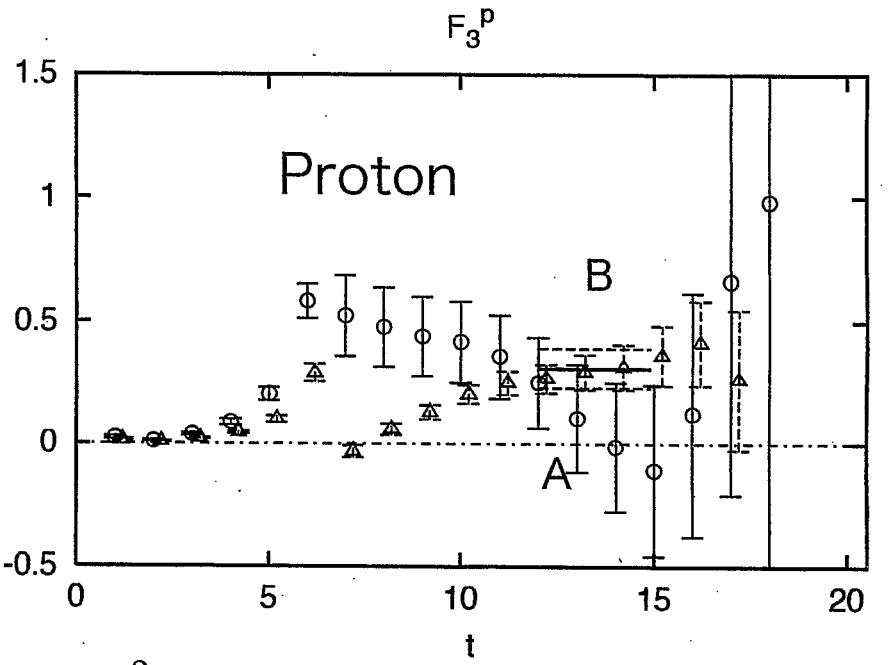


Quenched QCD with RG action $16^3 \times 32 \times 16,\ \beta = 2.6 (a \simeq 0.1\text{fm})$

domain-wall quarks(chiral symmetry) $m_f a = 0.03,\ \ m_\pi/m_\rho \simeq 0.62$

$F_3(q^2)$ from two extractions (A, B)





Preliminary

$q^2 \simeq 0.58\mathrm{GeV}^2$

$$\frac{1}{2m_N} F_3^n(q^2) = -2.4(4) \times 10^{-15} e \cdot \mathrm{cm}$$

$$\frac{1}{2m_N} F_3^p(q^2) = 2.2(6) \times 10^{-15} e \cdot \mathrm{cm}$$

$q^2 \to 0$?

cf. Crewther-DiVicchia-Veneziano-Witten: $|d_n| = +3.6 \times 10^{-16} e \cdot \mathrm{cm}$

NEDM from Energy Shift

- spin-dependent energy shift in the presence of the constant electric fields

$$m^{\uparrow}_{N^\theta}(\vec{E}) - m^{\downarrow}_{N^\theta}(\vec{E}) = 2\vec{d_n}(\theta)\cdot\vec{E} = 2\theta\vec{d_n}\cdot\vec{E} + O(\theta^2)$$

1989: Aoki-Gocksch

- real electric field in link variables $U_k(x) \to e^{qE_k t}U_k(x), \quad k = 1,2,3$

  O Periodicity in time is broken $\to |E| \ll 1$ $\quad a^2E = 0.004$

- no disconnected loops, no $q^2 \to 0$ extrapolation

Simulation parameters are same except $m_f a = 0.12, m_\pi/m_\rho \simeq 0.62$

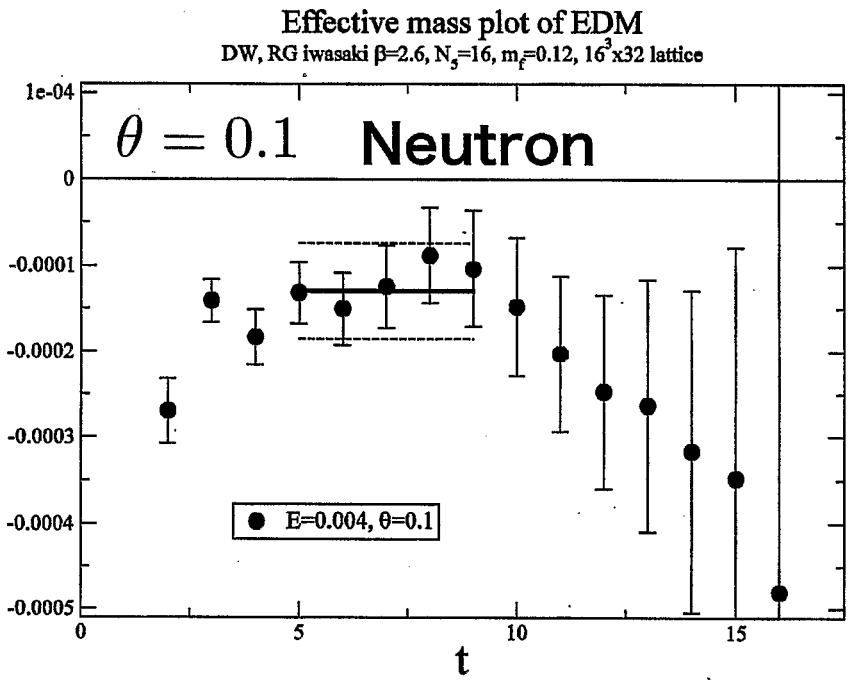
$$R(E_z,\theta;t) = \frac{G^\theta_{NN}(t,E_z)_{11}}{G^\theta_{NN}(t,E_z)_{22}} = Z\exp[-d^\theta_n E_z t] + \cdots$$

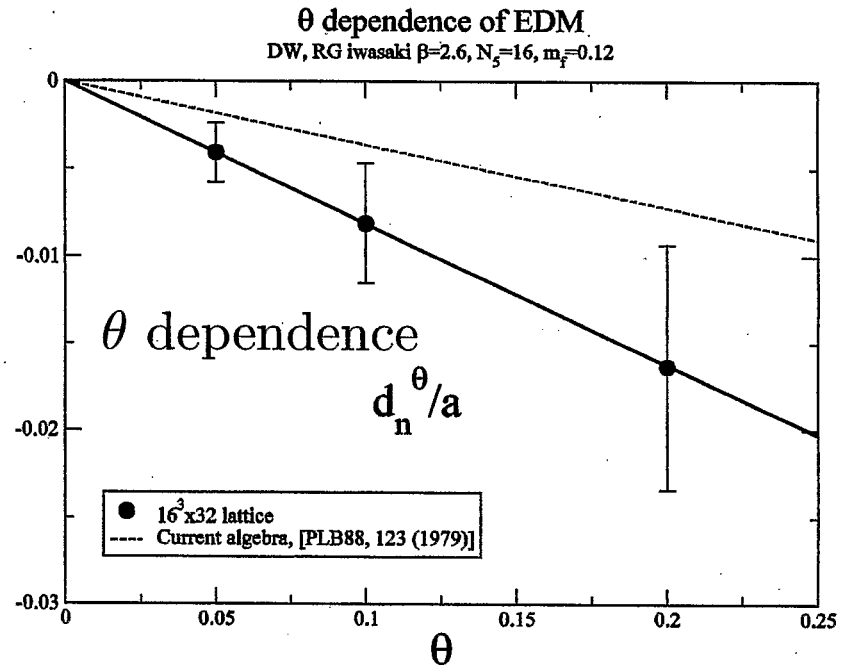
$$\vec{d_n}(\theta) = d^\theta_n\vec{\sigma}$$

$$G^\theta_{NN}(t,E_z) = \sum_Q \langle 0|N(t)\bar{N}(0)|0\rangle(E_z)e^{i\theta Q}$$

reweighting in Q

Preliminary results





Preliminary results

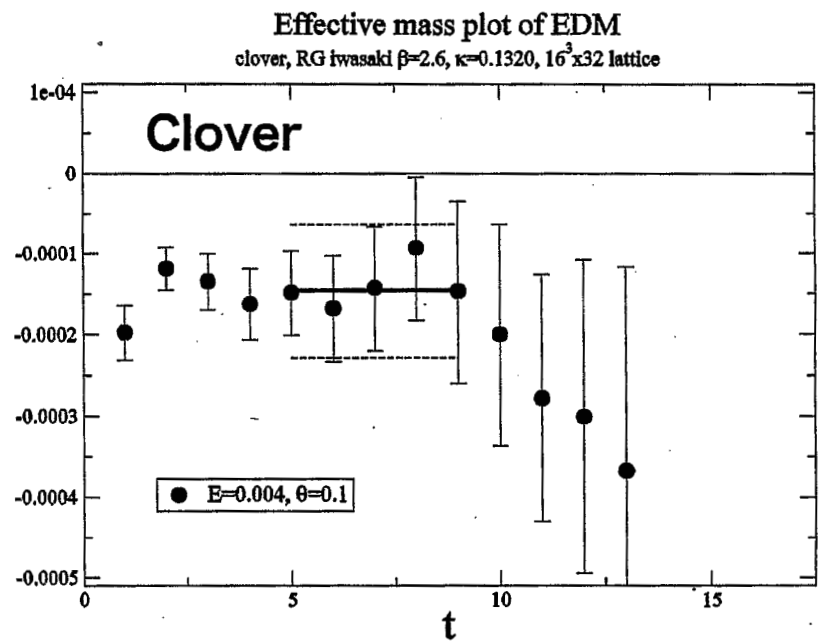
$$\begin{cases} d_n &= -1.6(6) \times 10^{-15} e \cdot \mathrm{cm} \\ d_p &= 1.6(8) \times 10^{-15} e \cdot \mathrm{cm} \end{cases}$$

$$\boxed{\begin{cases} F_3^n(q^2)/2m_N &= -2.4(4) \times 10^{-15} e \cdot \mathrm{cm} \\ F_3^p(q^2)/2m_N &= 2.2(6) \times 10^{-15} e \cdot \mathrm{cm} \end{cases}}$$

cf. Crewther-DiVicchia-Veneziano-Witten: $|d_n| = 3.6 \times 10^{-16} e \cdot \mathrm{cm}$

Our full QCD configurations are generated by Clover quarks.
Does this method work for Clover quarks ?

The method works also for Clover fermion !



Conclusions

- The 1st method(EDM form factor) works with quenched DWF.
- The 2nd method(Energy shift) also works.
  - O quenched DWF
  - O quenched Clover fermion
- Future works by the 2nd method
  - O lighter quark mass in quenched Clover Fermion
  - ☆ NEDM by Clover fermion on 2 and 2+1 flavor dynamical configurations of CP-PACS/JLQCD

RESEARCH SUMMARY
THEORY

Activity Report in the Year 2005

Taku Izubuchi

Taku Izubuchi's activity report in the year of 2005

- Finalizing the project of two flavour, $N_F = 2$, dynamical domain wall fermion (DWF) [4].
- Flavor singlet meson η' spectrum on $N_F = 2$ DWF configuration [7].
- Analysis of effective theory (chiral perturbation theory) in the case of mixed action, in which two different discretization are used for sea quark and valence quark[3][5].
- Quark mass determination for $N_F = 2$ DWF configuration[8] (summarized in this proceedings).
- QED effects, especially for mass splitting, between charged and neutral particles in pseudo scalar meson and nucleon[1][9].
- Hadronic contribution in muon anomalous magnetic moment, especially for light-by-light contribution[2][9].
- Review talk and its proceedings for lattice QCD Hadron spectrum at Lattice 2005 conference (Dublin) [8].
- $N_F = 2 + 1$ dynamical DWF project, especially for analysis of static quark potential and meson spectrum[7].

Light quark masses

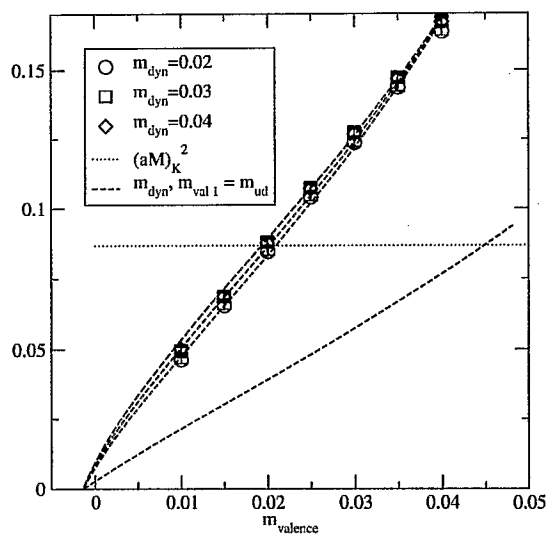
Quark mass is a fundamental parameter of the standard model Lagrangian, which is not directly accessible from experiments due to confinement.

- Lattice QCD : map between hadronic observables (hadron mass, decay constant) and quark mass,

$$M_{had}(m_q) = M_{had}^{(exp)}$$

- fix lattice scale, a^{-1} (Sommer scale r_0, m_ρ, f_π)
- Extrapolate to chiral regime ($m_{u,d} \sim \mathcal{O}(1)$ MeV).
- mass renormalization, Z factors, for non-lattice community.
- Extrapolate to continuum ($a \longrightarrow 0$).

map between hadronic mass and quark mass on lattice



- Set lattice scale, a^{-1}, from m_ρ, r_0, or f_π.
- quark mass at physical Kaon mass (horizontal line)
- By using non-degenerate ChPT formula (red dots), $am_{strange} = 0.0446(29)$ is extracted.
- If one uses dynamical, $m_{sea} = m_{val}$, points instead of $N_F = 2$ sea quarks, one finds $am_{strange} = 0.04177(64)$, 7% smaller than partially quenched analysis.

NPR(RI-MOM) on dynamical lattice

- measure quark propagator, $S_F(q)$, on Landau gauge fixed gauge configuration.
- calculate amputated green function of bilinear operators, $\Gamma = 1, \gamma_5, \gamma_5\gamma_\mu, \cdots$

$$\Pi_\Gamma = \langle u(-p)[\bar{u}\Gamma d]\bar{d}(q)\rangle_{AMP}$$

$$\Lambda_\Gamma = \left.\frac{\mathrm{Tr}\,(\Gamma\Pi_\Gamma)}{\mathrm{Tr}(\Gamma\Gamma)}\right|_{p^2,q^2=\mu^2}$$

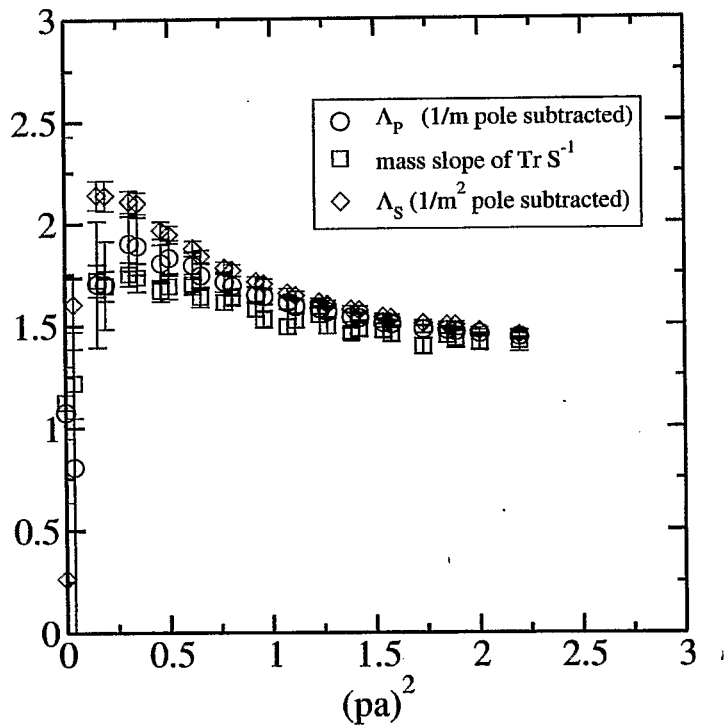
on lattice ensemble.

- Subtract mass pole to avoid non-perturbative effects ($\langle\bar{q}q\rangle$) by fitting

$$\Lambda_{\gamma_5} = \frac{c_1}{m_q} + \frac{Z_q}{Z_P} + c_3 m_q + \cdots$$

at $\Lambda_{QCD} \ll |p| \ll a^{-1}$ on each sea quark ensemble.
(Z_q quark field normalization, $Z_{P,S,A}$ pseudoscalar, scalar, axial current)

NPR(RI-MOM) on dynamical lattice...



- $\Lambda_P \approx \Lambda_S \approx \partial S^{-1}/\partial m \rightarrow \frac{Z_q}{Z_P}$
- convert from RI to $\overline{MS}$ with $c(pa)^2$ subtraction.
- constant fit all m_{sea} (mild dependency).
- $Z_P = 0.62(5)$
  (250 MeV $\leq \Lambda_{QCD} \leq$ 300 MeV)
- <u>preliminary results from $N_F = 2$ DWF:</u>

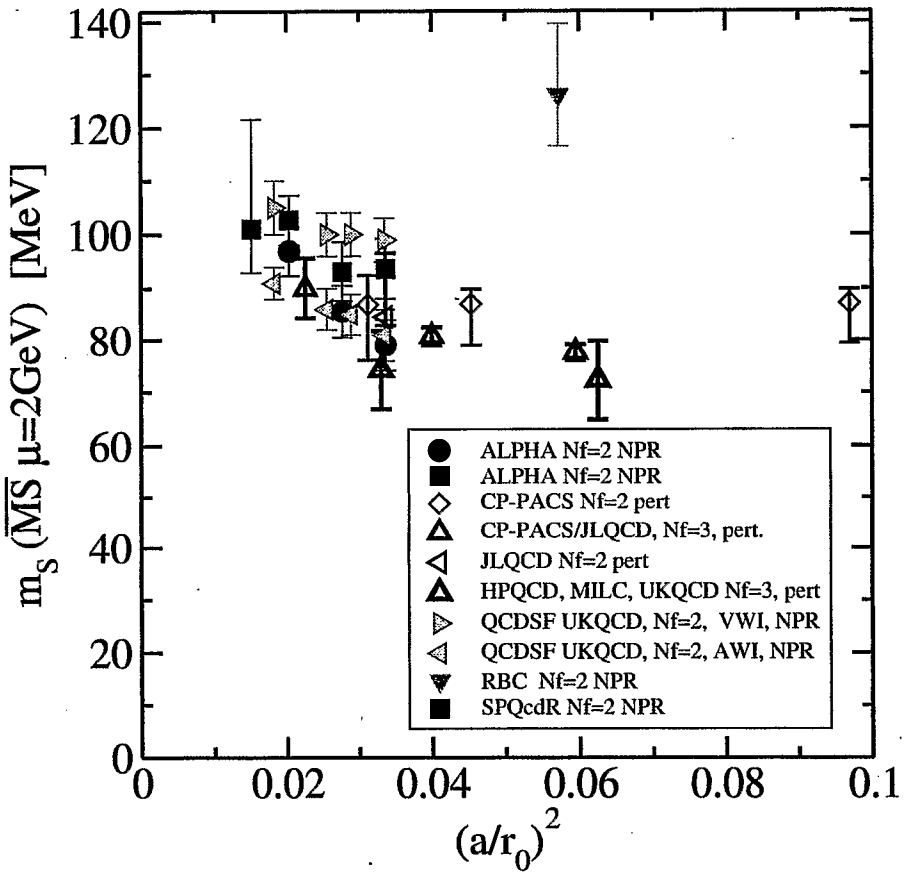
$$m_s = 126(9) \begin{pmatrix} +10 \\ -3 \end{pmatrix} \text{MeV}$$

$$\overline{m} = 4.21(33) \begin{pmatrix} +23 \\ -10 \end{pmatrix} \text{MeV}$$

- The second errors are due to difference between Z_P and Z_S, also Λ_{QCD} dependence.

recent dynamical strange quark masses

Preliminary



status of quark mass determination

- $N_F = 2, 3$ (difference is small in CP-PACS/JLQCD)
- scale is $r_0 = 0.5$ fm. (MILC corresponds to $\underline{r_0 = 0.467}$ fm, not corrected)
- uncertainties from chiral extrapolation ?
- operator renormalization from perturbative calculation tends to give smaller Z_m ?

DWF	NPR	Pert (K_c)
$Z_{V,A}$	0.7574(1)	0.770
$Z_{S,P}$	0.62(5)	0.847

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[9] T. Izubuchi "Electromagnetic splittings and $g_\mu - 2$ light-by-light contribution" talk given at 2nd ILFT workshop "From Actions to Experiment" at Edinburgh 07-10 March.

2004/2005 Progress Report

Steffen A. Bass

2004/2005 Progress Report

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In the following, I briefly outline the main research projects I have been involved in since the last RIKEN-BNL Research Center Review in November of 2004:

I. THE PARTON RECOMBINATION MODEL

Recent data from the Relativistic Heavy Ion Collider (RHIC) have shown a strong nuclear suppression of the pion yield at transverse momenta larger than 2 GeV/c in central Au + Au collisions, compared to $p+p$ interactions [1]. This is widely seen as the experimental confirmation of jet quenching, the phenomenon that high energy partons lose energy when they travel through the hot medium created in a heavy ion collision [2–4], entailing a suppression of intermediate and high P_T hadrons.

However, the experiments at RHIC have provided new puzzles. The amount of suppression seems to depend on the hadron species. In fact, in the production of protons and antiprotons between 2 and 4 GeV/c the suppression seems to be completely absent. Generally, pions and kaons appear to suffer from a strong energy loss while baryons and antibaryons do not. Two stunning experimental facts exemplify this [5–8]. First, the ratio of protons over positively charged pions is equal or above one for $P_T > 1.5$ GeV/c and is approximately constant up to 4 GeV/c. Second, the nuclear suppression factor R_{AA} below 4 GeV/c is close to one for protons and lambdas, while it is about 0.3 for pions.

There have been recent attempts to describe the different behavior of baryons and mesons through the existence of gluon junctions [9] or alternatively through recombination as the dominant mechanism of hadronization [10–12]. The recombination picture has attracted additional attention due to the observation that the elliptic flow pattern of different hadron species can be explained by a simple recombination mechanism [13–15]. The anisotropies v_2 for the different hadrons are compatible with a universal value of v_2 in the parton phase, related to the hadronic flow by factors of two and three depending on the number of valence

quarks [16].

The competition between recombination and fragmentation delays the onset of the perturbative/fragmentation regime to relatively high transverse momentum of 4–6 GeV/c, depending on the hadron species, providing a natural explanation for the aforementioned phenomena. To this date, parton recombination has developed into the most successful model for describing hadron production at RHIC in the intermediate transverse momentum domain.

A. Two-Particle Correlations

One of the biggest challenges for the recombination models to date has been the measurement of dynamic two-particle correlations. The picture of quarks recombining from a collectively flowing, deconfined thermal quark plasma appears to be at odds with the observation of "jet-like" correlations of hadrons observed in the same transverse momentum range of 2 to 5 GeV/c [17, 18]. The experiments at RHIC measure the associated particle yield per trigger hadron A. After subtracting the uncorrelated background and using the notation $\Delta\phi = |\phi_A - \phi_B|$, the relevant observable is defined as

$$Y_{AB}(\Delta\phi) = N_A^{-1}\left(\frac{dN_{AB}}{d(\Delta\phi)} - \frac{d(N_A N_B)}{d(\Delta\phi)}\right). \tag{1}$$

Triggering on a hadron, e.g., with transverse momentum 2.5 GeV/$c < p_T <$ 4 GeV/c, the data shows an enhancement of hadron emission in a narrow angular cone around the direction of the trigger hadron in a momentum window below 2.5 GeV/c. Can such correlations be reconciled with the claim that hadrons in this momentum range are mostly created by recombination of quarks?

Obviously, the existence of such correlations is incompatible with any model assuming that no correlations exist among the quarks before recombination, since such correlations require deviations from a global thermal equilibrium in the quark phase. However, it can be shown that correlations among partons in a quark-gluon plasma naturally translate into correlations between hadrons formed by recombination of quarks [19]. Correlations are even enhanced by an amplification factor $Q = n_A n_B$ similar to the scaling of elliptic flow. The interaction of hard partons with the medium has been discussed as one plausible mechanism for the existence of such parton correlations, even though other scenarios for the creation

of parton-parton correlations in the deconfined phase are possible. A numerical example displayed in figure 1 shows that two-parton correlations of order $\approx 10\%$ will be sufficient to explain hadron correlations as measured by the PHENIX collaboration. One may conclude that the existence of localized angular correlations among hadrons are not in contradiction with the recombination scenario but rather indicative for the existence of correlations among quarks prior to hadronization.

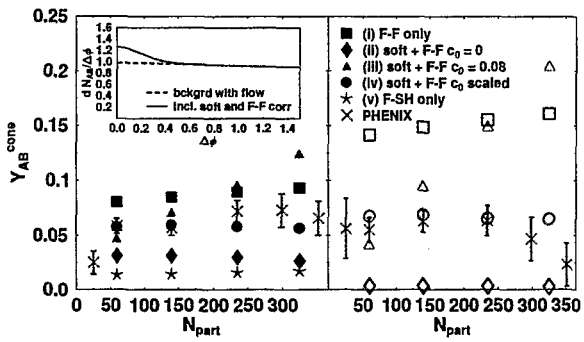

FIG. 1: $Y_{AB}^{\rm cone}$ which is Y_{AB} integrated over $0 \leq \Delta\phi \leq 0.94$, for meson (left panel) and baryon triggers (right panel) as a function of centrality. The inset shows the associated yield as a function of $\Delta\phi$ at an impact parameter $b = 8$ fm.

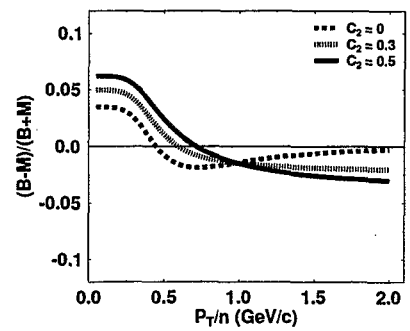

FIG. 2: Relative difference $(\tilde{v}_2^{(B)} - \tilde{v}_2^{(M)})/(\tilde{v}_2^{(B)} + \tilde{v}_2^{(M)})$ between the scaled meson and baryon elliptic flow for three different sizes of the higher Fock state component.

B. Beyond the Valence Quark Approximation

Recombination models usually are based on the concept of *constituent quark recombination*, which assumes that the probability for the emission of a hadron from a deconfined medium is proportional to the probability for finding the valence quarks of the hadron in the density matrix describing the source. The baryon enhancement, as well as the different momentum dependence of meson and baryon anisotropies, rely essentially on the different number of valence quarks in mesons (two) and baryons (three). The simplicity of this concept has been criticized, because it does not do justice to the complexity of the internal structure of hadrons in quantum chromodynamics (QCD). The question is how a more realistic treatment of the internal structure of hadrons in QCD affects these observables.

In the light-cone frame, where formally the hadron momentum $P \to \infty$ and the momentum fractions of the partons are the only dynamic degrees of freedom, a meson M with valence quarks q_α and $\bar{q}_\beta$ can then be written as an expansion in terms of increasingly complex Fock states:

$$\begin{aligned} |M\rangle &= \int_0^1 dx_a dx_b \delta(x_a + x_b - 1) c_1(x_a, x_b) \, |q_\alpha(x_a)\bar{q}_\beta(x_b)\rangle \\ &+ \int_0^1 dx_a dx_b dx_c \delta(x_a + x_b + x_c - 1) c_2(x_a, x_b, x_c) \, |q_\alpha(x_a)\bar{q}_\beta(x_b) g(x_c)\rangle \\ &+ \int_0^1 dx_a dx_b dx_c dx_d \delta(x_a + x_b + x_c + x_d - 1) c_3(x_a, x_b, x_c, x_d) \, |q_\alpha(x_a)\bar{q}_\beta(x_b) q_\gamma(x_c)\bar{q}_\gamma(x_d)\rangle + \ldots \end{aligned} \tag{2}$$

It has been shown [20] that the yield of relativistic parton clusters is independent of the number of partons in the cluster. Therefore, hadron spectra remain unaffected by the inclusion of a higher Fock state with an additional gluon. One important implication is that gluon degrees of freedom could be accommodated during hadronization. They simply become part of the quark-gluon wave functions of the produced hadrons, but remain hidden constituents because the commonly produced hadrons do not contain valence gluons.

However, higher Fock states introduce deviations from the scaling law for elliptic flow. Using a narrow wave function limit, one can easily generalize the well-known valence quark scaling law to higher Fock states:

$$v_2^{(\mathrm{H})}(P) \approx \sum_\nu |c_\nu|^2 n_\nu v_2(P/n_\nu) \tag{3}$$

Figure 2 shows the relative difference $(\tilde{v}_2^{(\mathrm{B})} - \tilde{v}_2^{(\mathrm{M})})/(\tilde{v}_2^{(\mathrm{B})} + \tilde{v}_2^{(\mathrm{M})})$ between the scaled meson and baryon elliptic flow for three different sizes of the higher Fock state component (0%, 30%, 50%). In all cases, baryons have a slightly larger scaled $\tilde{v}_2$ than mesons at small momenta. This effect is likely to be overwhelmed by the influence of mass differences, which have been neglected in the sudden recombination model. At larger momenta, the scaled meson $\tilde{v}_2$ is slightly larger. In principle, these violations on the order of $\sim 10\%$ should be visible in a scaling analysis and first observations along these lines have been reported at this meeting [21].

It should be emphasized that the interpretation of elliptic flow data from RHIC proving the existence of quark degrees of freedom in the bulk matter is still valid. However, the connection of the measured elliptic flow to the quark elliptic flow might be less straight forward than anticipated.

II. A NOVEL HYDRO+MICRO TRANSPORT APPROACH

Hybrid macroscopical/microscopical transport models, employing hydrodynamics for the early dense reaction phase and microscopic non-equilibrium dynamics for the later, dilute reaction stages are particularly well suited for the investigation of the QGP equation of state as well as hadronic final state interactions in the SPS, RHIC and LHC energy domains. Together with a collaborator I have been at the forefront of the development of this novel class of transport models [22], and research along this very promising approach has been rapidly expanding [23–26].

The applicability of our original hybrid micro/macro model [22] used for previous studies is hampered by the hydrodynamic component only utilizing a boost-invariant 1+1 dimensional calculation, which does not allow for calculations of elliptic flow or quantities away from mid-rapidity. Therefore we are currently undertaking the extension of the hydrodynamical component of our model to a fully three dimensional hydrodynamics code [27]. Progress in the development of a full 3D hydrodynamical model has been slower than originally anticipated, in particular concerning the development of the interface between the hydrodynamical model and the microscopic transport in the hadronic phase. However, significant progress has been made over the past 2-3 months: we now have both, a fully working 3D hydrodynamical model and an interface to UrQMD and are currently in the process of determining the initial conditions necessary for addressing the RHIC data. Note that two different sets of initial conditions will need to be found – one for the application of the purely hydrodynamic approach and one for the combined macro+micro approach. It is our goal to find a set of initial conditions for both approaches (stand-alone hydrodynamics as well as the hybrid hydro+UrQMD approach) which will allow us to consistently describe all aspects of the low to intermediate transverse momentum physics data at RHIC – most importantly identified hadron spectra, elliptic flow, (pseudo-)rapidity distributions as well as two particle correlations. It should be noted that the much celebrated current success of hydrodynamics at RHIC has come at the expense of using different initial conditions for the description of spectra and elliptic flow – it is our intention to significantly improve upon this unsatisfactory situation.

Once we have demonstrated the functionality of our model in addressing the current RHIC data, we intend to follow our proposed project by investigating

- the sensitivity of hadronic observables (e.g. v_2, m_T-spectra and particle-yields) on the QGP equation of state and the critical temperature T_C.

- radial flow expansion parameters and v_2 coefficients of multi-strange baryons for different initial conditions: since multi-strange baryons are thought to decouple early from the hadronic evolution of the system (due to their small hadronic cross sections), they are expected to yield a direct probe of the collective expansion of the system at the hadronization hypersurface. Collision rates and freeze-out time distributions of multi-strange baryons will be calculated to verify/falsify the conjecture of early decoupling at the phase-boundary.

- HBT interferometry: all current hydrodynamic calculations have failed to reasonably describe the measured RHIC HBT data, giving rise to the so-called *HBT puzzle at RHIC*. Utilizing a 3D-hydro without any assumptions on boost-invariance for the calculation of the correlation functions will allow us to determine whether the previous failure of hydrodynamics in the HBT sector is due to simplifying assumptions such as boost-invariance or due to more general features of the hydrodynamic evolution (such as an overestimation of the lifetime of the system).

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Research Summary

Takanori Sugihara

Matrix product representation of gauge invariant states in a Z_2 lattice gauge theory

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The importance of the first-principle study in quantum chromodynamics is increasing largely because RHIC experiment has started and LHC is also coming. For precise description of high-energy heavy ion collisions, gauge theory needs to be studied at finite temperature and density in a systematic way. Lattice gauge theory is the most useful method for studying the quark-gluon systems at zero and finite temperature. However, Monte Carlo integration does not work for lattice gauge theory with large chemical potential because of the severe sign problem. It would be worthwhile to pursue a systematic variational approach to gauge theory. In this work, we propose an efficient variational method for Z_2 lattice gauge theory based on the matrix product ansatz. The method is applied to ladder and square lattices. The Gauss law needs to be imposed on quantum states to guarantee gauge invariance when one studies gauge theory in hamiltonian formalism. On the ladder lattice, we identify gauge invariant low-lying states by evaluating expectation values of the Gauss law operator after numerical diagonalization of the gauge hamiltonian. On the square lattice, the second order phase transition is well reproduced. The obtained value of the critical coupling is $\lambda \sim 3.12$, which is close to the past numerical results. However, our lattice size $L = 12$ is still small. Further refinement will be given elsewhere.

References

[1] T. Sugihara, *Matrix product variational formulation for lattice gauge theory*, AIP Conf. Proc. 756, 305 (2005).

[2] T. Sugihara, *Matrix product representation of gauge invariant states in a Z_2 lattice gauge theory*, JHEP 0507:022 (2005).

[3] T. Sugihara, *Gauge invariance in a Z_2 hamiltonian lattice gauge theory*, hep-lat/0509045.

QCDSP/QCDOC PHYSICS RESULTS AND PROSPECTS/PROJECT STATUS

QCDOC Overview

Nicholas P. Samios

Computing at RBRC

QCDSP	Funded by RIKEN
	0.6 teraflops
	Operational 1998 -
	Efficiency >99%
QCDOC	Funded by RIKEN
	10 teraflops
	Dedicated May 2005
	Operational 2005 -

Other

DOE QCDOC 10 teraflops Operational

UK QCDOC 10 teraflops Operational

Utilized by RBRC Physicists

Administration of RBRC QCDOC

Responsible Individual RBRC Director

QCDOC Collaboration

RBRC, Columbia University, BNL and U.K.

Regular Meetings

Physics, Schedules. Etc/

Director's Committee:

N.P. Samios, L. McLerran, N. Christ, R. Mawhinney

Six-Week Intervals

Physics, schedules, allotment of resources

Oversight Committee:

S. Aoki, M. Creutz, R. Pisarski

Reports to Director on QCDOC Operations

RBRC QCDOC Machine Usage

Rack	June 28, 2005	July 19, 2005	August 9, 2004	August 30, 2005
ACC0 (CU)	NPR, heavy quark action (HW. Lin)	NPR, heavy quark action (HW. Lin)	NPR, heavy quark action (HW. Lin)	NPR, heavy quark action (HW. Lin)
Rack 2 (CU)	K->pi+pi, quenched, DWF, (Yamazaki)	p4 action scaling (Cheng)	K->pi pi, DWF, (Takeshi)	K->pi pi, DWF, (Takeshi)
Rack 3 (CU)	N_f=2+1, DWF, (S.Li)	N_f=2+1, DBW2, B_K (Cohen)	N_f=2+1, DBW2, B_K checking (Saul)	N_f=2+1, DBW2, B_K checking (Saul)
Rack 4 Rack 5 Rack 6 Rack 7	N_f=2+1, DWF (MF. Lin)	N_f=2+1, DWF (MF. Lin)	N_f=2+1, DWF 0.03/0.04, evolution (Mawhinney)	N_f=2+1, DWF 0.03/0.04, evolution, 240 trajs (Mawhinney)
Rack 8 Rack 9 Rack 10 Rack 11	N_f=2+1 DWF (MF. Lin)	N_f=2+1 DWF (MF. Lin)	N_f=2+1, DWF, 0.02/0.04, evolution (MF. Lin)	N_f=2+1, DWF, 0.02/0.04, 570 trajs (MF. Lin)
Rack 12		QCD thermo, N_t=6 spectrum (Petrov)	QCD thermo, N_t=6 spectrum (Petrov)	QCD thermo N_t=6, N_f=3 \beta=2.725, m=0.02 (Chulwoo)
Rack 13	N_f=2+1, DWF (MF. Lin)	N_f=2+1, DBW2, beta=0.72, 0.01/0.04, evolution (MF Lin)	N_f=2+1, DBW2, beta=0.72, 0.01/0.04, evolution (MF. Lin)	N_f=2+1, DBW2, beta=0.72, 0.01/0.04, evolution (MF. Lin)
Rack 14	Being repaired	N_f=2+1, DBW2 spectrum (MF Lin)	N_f=2+1, 0.01/0.04, DBW2, \beta=0.72 spectrum (MF. Lin)	N_f=2+1, 0.01/0.04, DBW2, \beta=0.72 spectrum (MF. Lin)
Rack 15	QCD thermo (Schmidt) short jobs/code debugging (general)	QCD thermo (Schmidt) short jobs/code debugging (general)	QCD thermo (Schmidt), N_t=6 general usage	QCD thermo (Schmidt), N_t=6 general usage

RBRC QCDOC Machine Usage

Rack	September 13, 2005				
ACC0 (CU)	NPR, heavy quark action (HW. Lin)				
Rack 2 (CU)	K->pi+pi, quenched, DWF, (Yamazaki)				
Rack 3 (CU)	N_f=2+1, B_K (Cohen) and eignenvalue bound checking (MF Lin)				
Rack 4	N_f=2+1, DWF (Mawhinney) ml/ms=0.03/0.04, 250 trajectories				
Rack 5					
Rack 6					
Rack 7					
Rack 8	N_f=2+1 DWF (MF. Lin) ml/ms=0.02/0.04, 640 trajectoreis				
Rack 9					
Rack 10					
Rack 11					
Rack 12	QCD thermo, N_t=6 scale setting, \beta=2.744, N_f=3, m=0.02 (Jung)				
Rack 13	QCD thermo, 32^3x6, m=0.01 \beta=2.67 (Jung)				
Rack 14	QCD thermo, 32^3x6, m=0.01 \beta=2.66 (Jung)				
Rack 15	QCD thermo, 16^3x6, old p4 (Schmidt)				
	short jobs/code debugging (general)				
DOE usage	Rack 17	QCD thermo, N_t=6 old p4 (Schmidt)			
	Rack 18	QCD thermo, \beta=2.917, m=0.05 scale setting (Jung)			
	Rack 20/21	eta' mass (Izubuchi/Hashimoto),			

RBRC Lattice QCD - An Overview

Norman H. Christ

RBRC Lattice QCD --- an Overview

RBRC Review

October 11, 2005

Norman H. Christ

Outline

- QCDOC status
- Lattice configurations
- Physics topics
- 2- and 3-flavor simulations
- $K \rightarrow \pi + \pi$
- Heavy quarks
- Outlook

QCDOC Collaboration

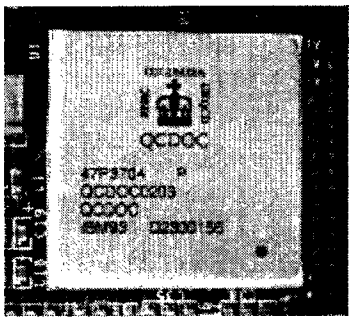
- Columbia (DOE)
  - Norman Christ
  - Saul Cohen
  - Calin Cristian
  - Zhihua Dong
  - Changhoan Kim
  - Ludmila Levkova
  - Xiaodong Liao
  - Meifeng Lin
  - Guofeng Liu
  - Robert Mawhinney
  - Shu Li
  - Azusa Yamaguchi
- BNL (SciDAC)
  - Chulwoo Jung
  - Konstantin Petrov
  - Stratos Efstathiadis
- UKQCD (PPARC)
  - Peter Boyle
  - Mike Clark
  - Balint Joo
- RBRC (RIKEN)
  - Shigemi Ohta
  - Tilo Wettig
- IBM
  - Dong Chen
  - Alan Gara
  - Design groups:
    - Yorktown Heights, NY
    - Rochester, MN
    - Raleigh, NC

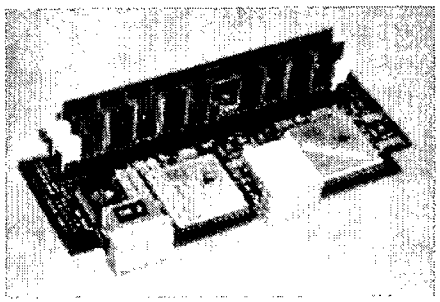
QCDOC Architecture

- IBM-fabricated, single-chip node. (50 million transistors, 5 Watt, 1.3cm x 1.3cm)
- Processor:
  - PowerPC 32-bit RISC.
  - 64-bit, 1 Gflops floating point unit.
- Memory/node: 4 Mbyte (on-chip) & 128 Mbyte DIMM.
- 6-dim communications network.
- Ethernet connection to each node.
- ~7-8 Watt/node, 15 in^3 per node.

QCDOC construction

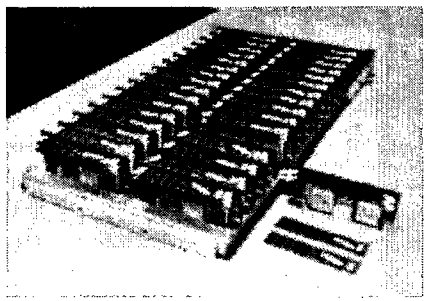
QCDOC ASIC (1 node) →

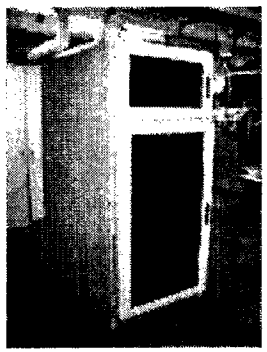




← Daughter board (2 nodes)

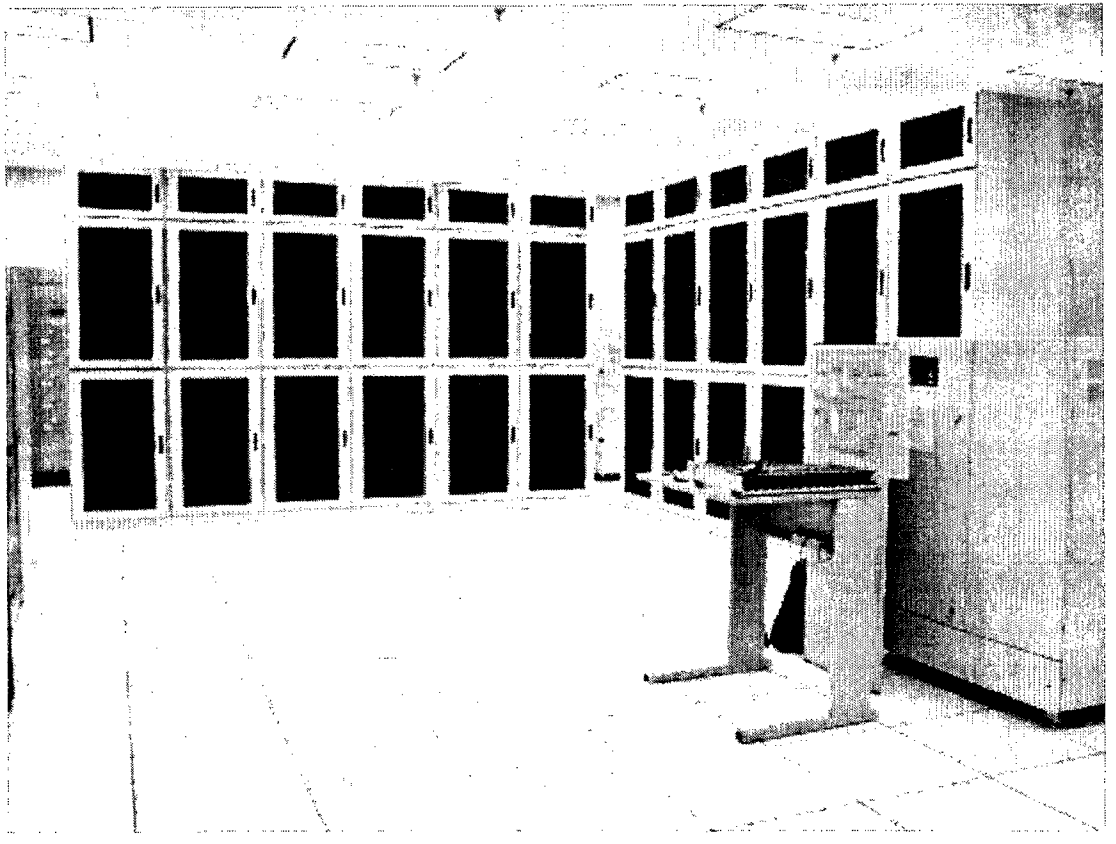
Mother board (64 nodes) →





← Rack (1024 nodes)

Brookhaven Installation



RBRC (right) and DOE (left) 12K-node QCDOC machines

QCDOC now in full production

- QCDOC dedicated May 2005
- First QCDOC results presented at Lattice 2005 in Dublin.
- Thanks for successful installation to BNL scientists and technical staff:

Ed Mcfadden
Eric Blum
Ed Brosnan
Christopher Channing
Andrew Como
Joe Depace
Efstratios Efstathiadis
Don Gates
Chulwoo Jung
Kostya Petrov
Paul Poleski

Led by Bob Mawhinney

Current QCDOC Usage

(September 13, 2005)

ACC0	½ rack-CU	NPR, heavy quark action (HW. Lin)
Rack 2	CU	K->pi+pi, quenched, DWF, (Yamazaki)
Rack 3	CU	N_f=2+1, B_K (Cohen) / eigenvalue tuning (MF Lin)
Racks 4-7	RBRC	N_f=2+1, DWF (Mawhinney) ml/ms=0.03/0.04
Racks 8-11	RBRC	N_f=2+1 DWF (MF. Lin) ml/ms=0.02/0.04
Rack 12	RBRC	QCD thermo, 16^3x32, p4fat7 scale setting (Jung)
Rack 13	RBRC	QCD thermo, 32^3x6, p4fat7, m=0.01 (Jung)
Rack 14	RBRC	QCD thermo, 32^3x6, p4fat7, m=0.01 (Jung)
Rack 15	RBRC	QCD thermo, 16^3x6, p4fat3 (Schmidt)/general use
Rack 17	DOE	QCD thermo, N_t=6, p4fat3 (Schmidt)
Rack 18	DOE	QCD thermo, 16^3x32, p4fat7 scale setting (Jung)
Rack 19	DOE	*Kl*3 decay (Sasaki)
Rack 20-21	DOE	η' mass (Izubuchi/Hashimoto),

RBC Collaboration

RBRC

Tom Blum (U. Conn.)
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Koichi Hashimoto
Taku Izubuchi (Kanazawa)
Shigemi Ohta (KEK)
Shoichi Sasaki
Takeshi Yamazaki

BNL

Michael Creutz
Saumen Datta
Chulwoo Jung
Frithjof Karsch
Takashi Kaneko
Jack Laiho (Fermilab)
Peter Petreczky
Konstantin Petrov
Christian Schmidt
Amajit Soni
Takashi Umeda

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Michael Cheng
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C.M. Maynard
R.J. Tweedie
A. Yamaguchi

Lattice Configurations

Action	Quark Flavors	Lattice spacing ($1/a$)	Volume	Parameters	# confs. / trajs.
DBW2	0	1.3 GeV	$16^3 \times 32$	$\beta = 0.87$	129
Wilson	0	1.4 GeV	$16^3 \times 32$	$\beta = 5.85$	91
Wilson	0	2.0 GeV	$16^3 \times 32$	$\beta = 6.0$	400
DBW2	0	2.0 GeV	$16^3 \times 32$	$\beta = 1.04$	202
DBW2	0	3.0 GeV	$24^3 \times 48$	$\beta = 1.22$	106
DBW2	2	1.7 GeV	$16^3 \times 32$	$\beta = 0.8$ m_{sea}=0.02/0.03/0.04	5000
DBW2	2+1	1.6 GeV	$16^3 \times 32$	$\beta = 0.72$ m_{ud}/m_s=(0.01,0.02,0.03)/0.04	6000
Iwasaki	2+1	1.8 GeV	$24^3 \times 64$	$\beta = 2.13$ m_{ud}/m_s=(0.01,0.02,0.03)/0.04	underway

Physics Topics

- Hadron spectrum.
- K meson decays
  - $\Delta = ½$ rule
  - ε'/ε
  - K^0–$\overline{K}^0$ mixing (B_K)
  - $Kl3$ decay
- Static quark potential
- Muon g-2
- Electromagnetic splittings
- η' mass
- $\pi + \pi$ phase shifts
- Nucleon structure
  - g_a
  - Structure functions
  - Excited states
- Heavy quarks
  - Charm spectrum
  - B-$\overline{B}$ mixing
- QCD at finite temperature
  - Properties of transition
  - Equation of state
  - Heavy quark systems
  - $\mu \neq 0$

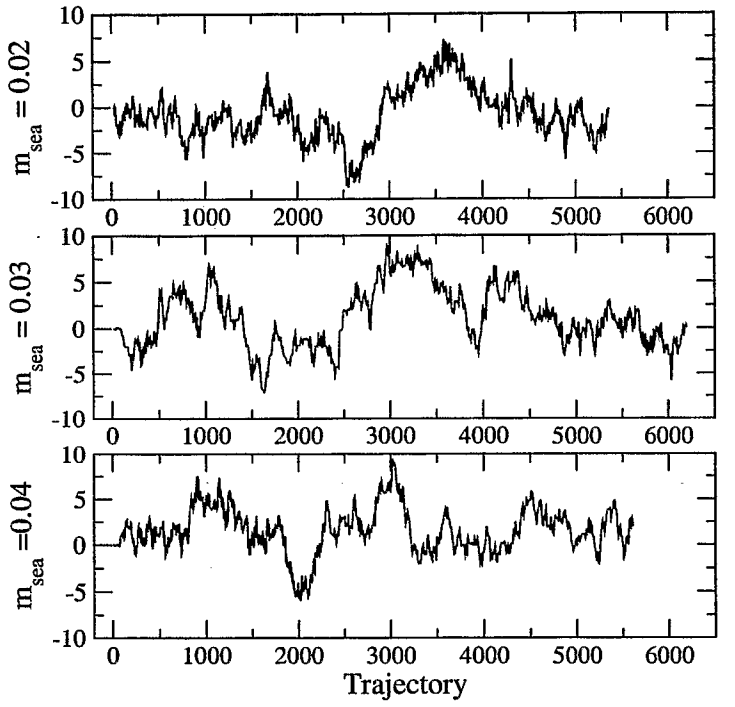
Two-flavor DWF simulations

- $16^3 \times 32$, L_s=12, $1/a$=1.7 GeV
- Provide gauge configurations used in many calculation
- **hep-lat/0411006**

$m_{ud}/m_s = 0.5$	5361 trajectories
$m_{ud}/m_s = 0.75$	6195 trajectories
$m_{ud}/m_s = 1.0$	5605 trajectories

(Relied on improved algorithms of Dawson and Izubuchi)

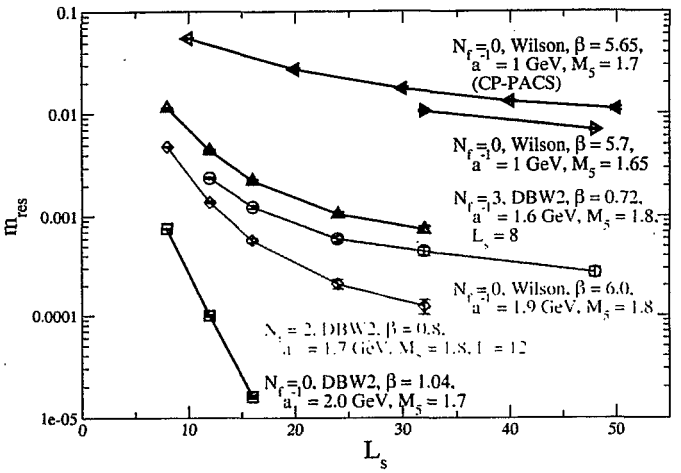
Evolution of topological charge



2+1 Flavor Simulations

(MF Lin, S. Cohen, R. Mawhinney and UKQCD)

- More quark flavors → rougher gauge fields and larger m_{res}.
- Explore a series of quark masses, lattice spacings and action variants to minimize this effect. (16^3 x 32, $L_s = 8$)



2+1 flavors, RHMC

β	c_1	m_l	m_h
0.72	-1.4069	0.01	0.04
0.72	-1.4069	0.02	0.04
0.72	-1.4069	0.04	0.04
0.764	-1.4069	0.02	0.04
0.764	-1.4069	0.04	0.04
0.78	-1.4069	0.02	0.04
0.78	-1.4069	0.04	0.04
2.13	-0.331	0.02	0.04
2.13	-0.331	0.04	0.04
2.2	-0.331	0.02	0.04
2.2	-0.331	0.04	0.04
2.3	-0.331	0.04	0.04

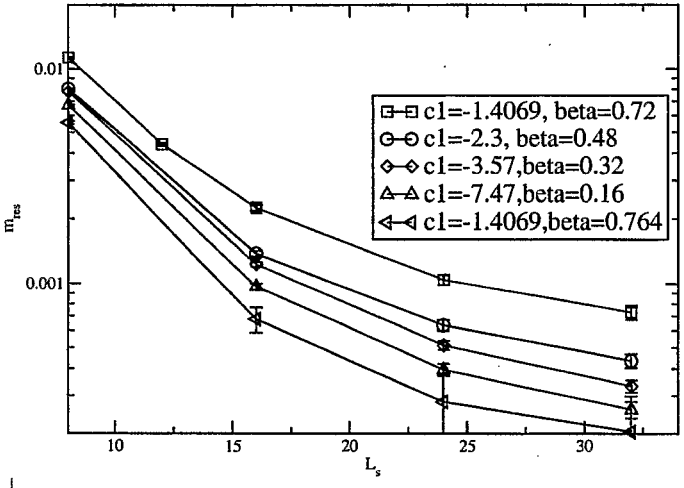
3 flavors, "R" algorithm

β	c_1	m_l	m_h
0.80	-1.4069	0.04	0.04
0.72	-1.4069	0.02	0.02
0.72	-1.4069	0.04	0.04
0.48	-2.3	0.04	0.04
0.32	-3.57	0.04	0.04
0.16	-7.47	0.04	0.04
0.53	-2.3	0.04	0.04
0.36	-3.57	0.04	0.04
0.33	-3.57	0.04	0.04

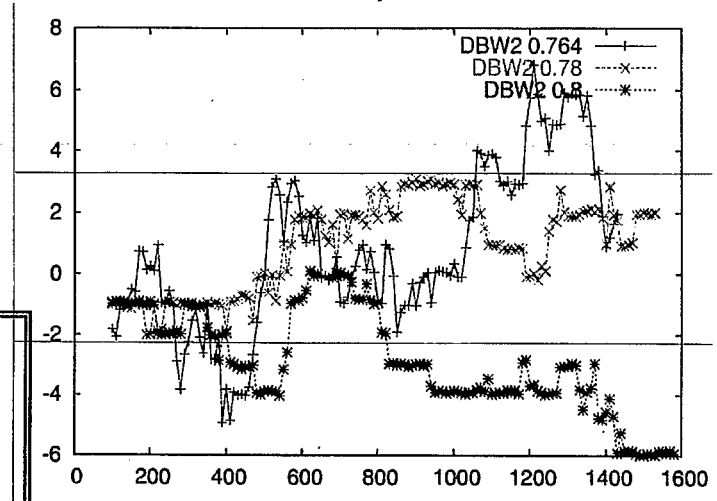
Results of Experiments

- Some improvement for large rectangle coefficient:

c_1	β	$m_{\rm res}$ $(m_f = 0)$	$m_\rho a$ $(m_f = -m_{\rm res})$	$a^{-1}(GeV)$
-1.4069	0.72	1.182(7)e-02	0.530(9)	1.45(2)
-2.3	0.48	8.04(6)e-03	0.534(8)	1.44(2)
-3.57	0.32	7.77(5)e-03	0.518(8)	1.49(2)
-7.47	0.16	6.70(10)e-03	0.542(7)	1.42(2)



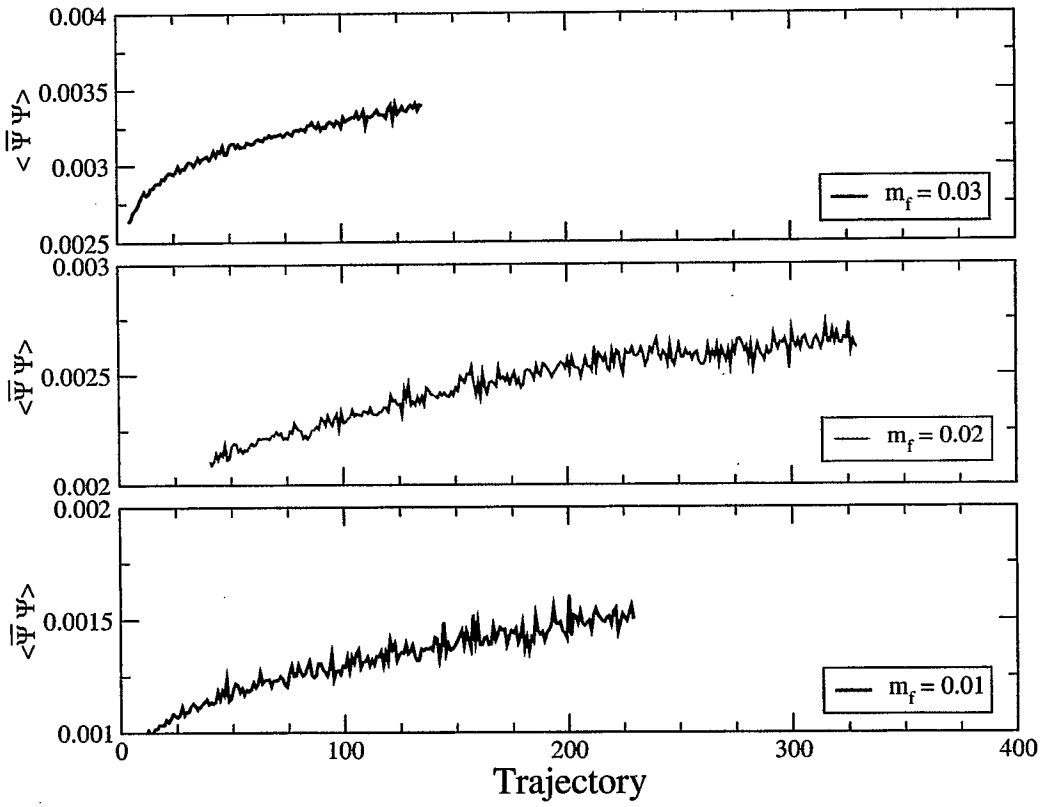
- Topological charge evolves very slowly for DBW2 action: *(A. Yamaguchi)*



Decide on Iwasaki action, β = 2.13 → 1/*a* ≅1.8 GeV, $m_{strange}$=0.04 and L_s=16

Generating N_f= 2+1 Configurations

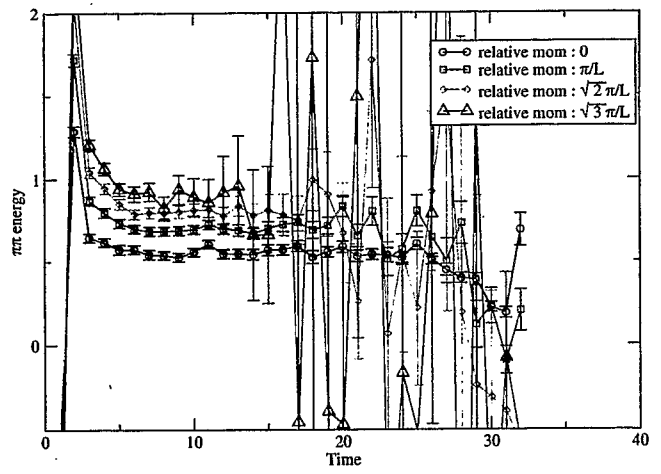
- 24^3 x 64 volume
- $m_{strange} \cong 0.04$
- $L_s = 16$
- $m_{res} \cong 0.002$
- $1/a \cong 1.8$ GeV
- 2.7 Fermi box
- Exact RHMC method (UKQCD)
- 4x RHMC speedup being implemented.

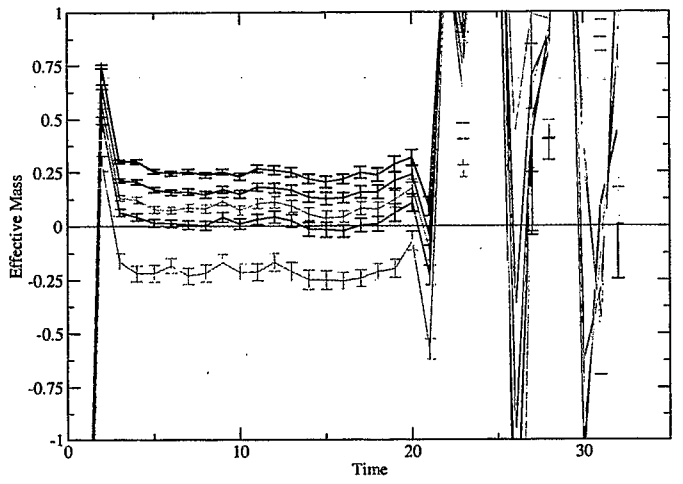


$K \rightarrow \pi + \pi$ *(Changhoan Kim)*

- Avoid the Miani-Testa theorem by imposing "anti-periodic" boundary conditions and using Lellouch-Luscher.
- Quenched, $1/a$=1.3 GeV, 16^3 x 32, DWF, L_s=12, 129 configurations.

In units of MeV	m_K	m_π	p_π
Simulation	910	352	290
Nature	496	138	206



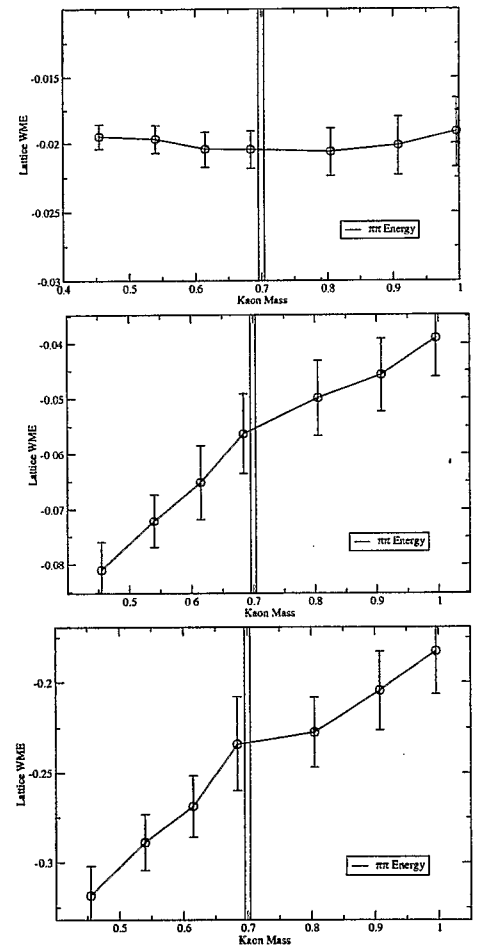


$K \rightarrow \pi + \pi$ *(Changhoan Kim)*

- Lattices doubled and data taken from both sides.
- Final pions projected onto non-zero momentum.
- Average over three choices for the anti-periodic direction.

	O_{27} x 100	O_{88} x 100	O_{88m} x 10
0	-1.230(24)	-8.22(17)	-2.989(59)
$\pi/16$	-2.114(60)	-6.88(23)	-2.815(85)
$2^{1/2}\pi/16$	-2.16(12)	-3.89(40)	-1.82(13)
$3^{1/2}\pi/16$	-2.30(35)	-1.8(10)	-1.40(32)

	Our result	Comparison	Note
O_{27}	7.30(28) 10^{-8}	1.497 10^{-8}	Expt.
$O_{88}+O_{88m}$	6.65(70) 10^{-12}	1.20(22) 10^{-11}	χPT



O_{27}

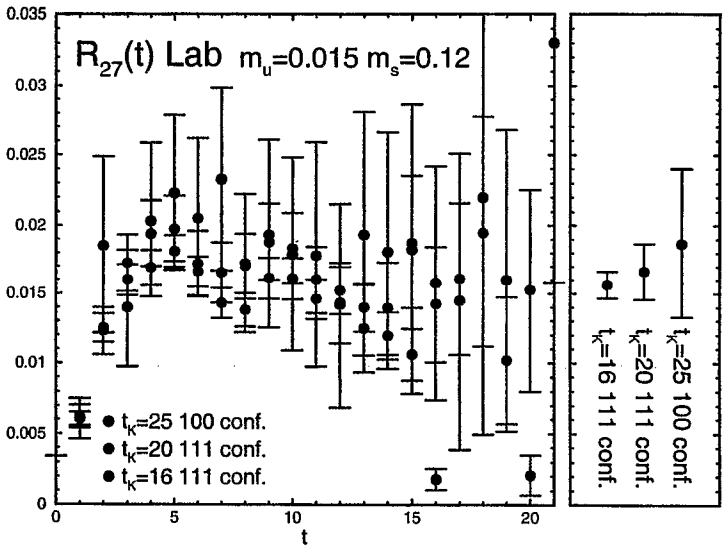
O_{88}

O_{88m}

$K \rightarrow \pi + \pi$ — $\Delta I = 1/2$?

(Takeshi Yamazaki)

- I = 0 final state.
  - Suppress unwanted $\pi + \pi$ states
  - Suppress vacuum state.
- Suppress unwanted $\pi^+ + \pi^-$ states
  - $(\overline{u}_A d_P)$ tricks don't work.
  - Use G-parity boundary conditions.
  - Must be dynamical to split $\eta + \eta$ state.
- Extend Luscher/ Lellouch-Luscher to $\vec{P}_{cm} \neq 0$ (**hep-lat/0507009**):

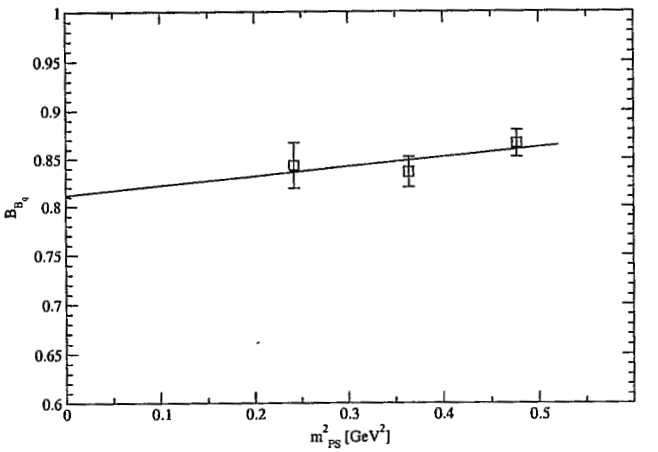


$$|A|^2 = 8\pi \frac{m_K^3}{k_{cm}^3} \gamma^2 \{ k \frac{\partial \delta}{\partial k} + q \frac{\partial \phi}{\partial q} \} |M|^2$$

Heavy quarks

- Charm physics using domain wall fermions. *(HW Lin, Ohta, Yamada)*
- B-$\overline{\text{B}}$ mixing using domain wall light quarks and "static" heavy quarks. *(Gadiyak, Loktik* hep-lat/0509075*)*
- Relativistic heavy quark action determined non-perturbatively. *(HW Lin, Christ)*

B-$\overline{\text{B}}$ mixing



Static approx, Nf = 2:

- $f_s / f_d = 1.29(4)(6)$
- $B_s / B_d = 1.06(6)(4)$
- $\xi = 1.33(8)(8)$

Non-perturbative calculation of RHQ action

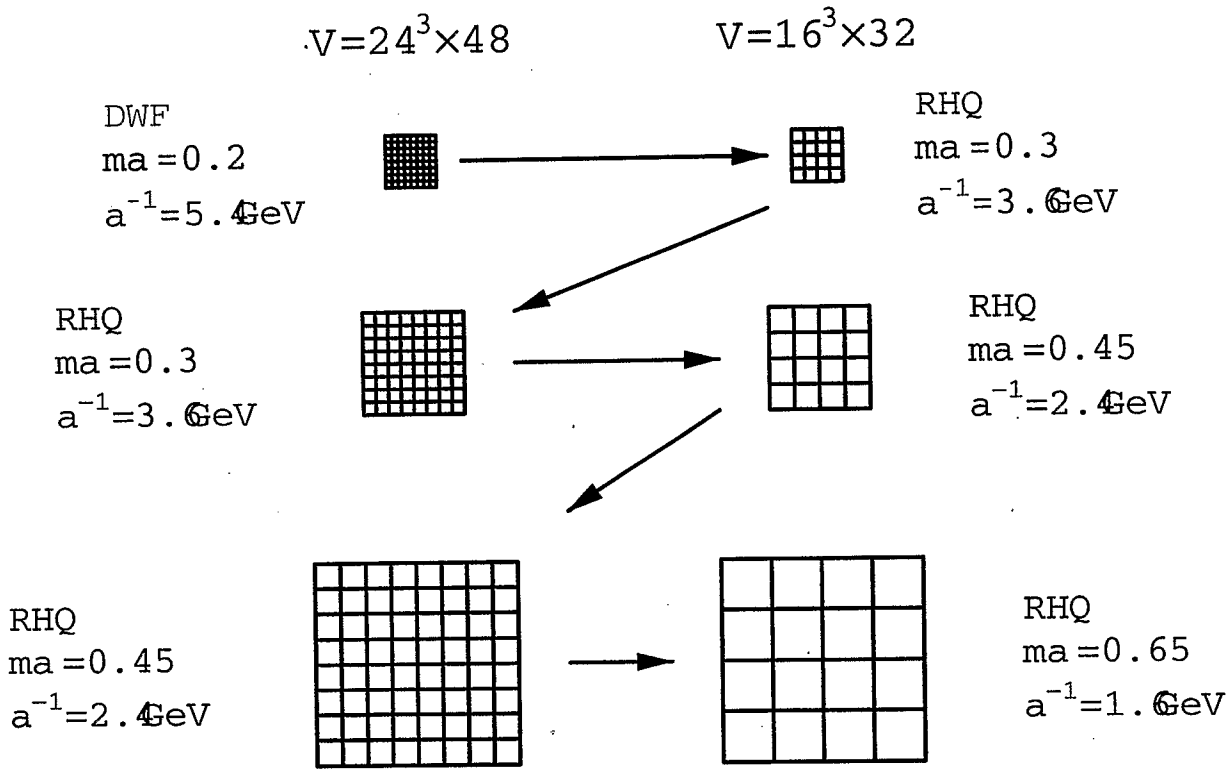
(HW Lin)

- Start with 7 parameters ($(ma)^n$ errors removed):

$$S = \sum_x \overline{\psi}(x)[m_0 + \gamma_0 D_0 + \zeta\vec{\gamma}\cdot\vec{D} - r_t D_0^2 - r_s \sum_i D_i^2$$
$$- \sum_i \frac{i}{2}\sigma_{0i}F_{0i} + \sum_{i,j}\frac{i}{2}c_B\sigma_{ij}F_{ij} + \xi\{D_0, D_i\}\sigma_{0,i}]\psi(x)$$

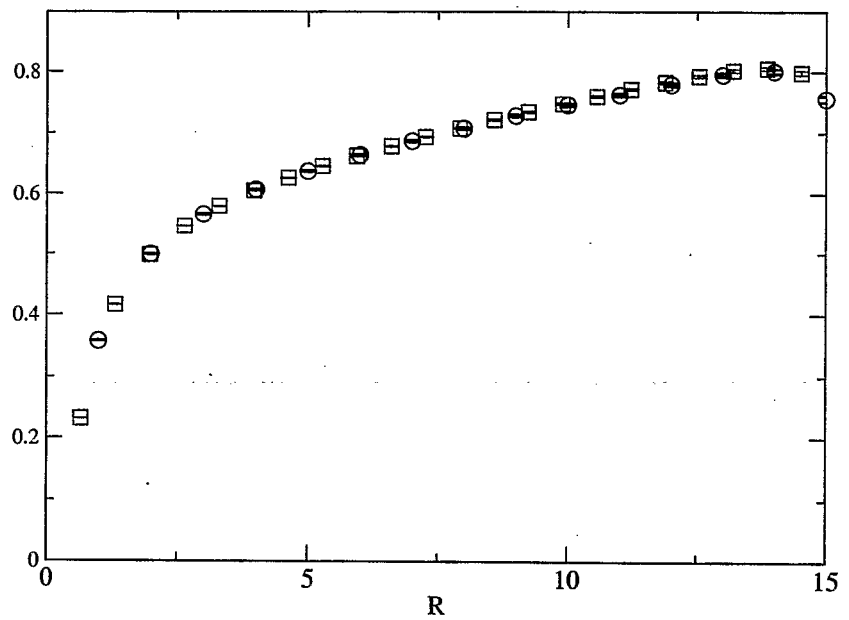
- Use EOM to set $r_t = 1$ and $\xi = 0$. (Aoki, *et al.*)
- Use field transformation to set $r_s = \zeta$. (Fermilab)
- Use step-scaling to connect small $1/a$=5.4 GeV lattice ($m_{\text{charm}} << 1/a$) with $1/a$=2.4 GeV lattice.
- Match hh and hl spectrum as well as fix m_1/m_2=1.

Step-scaling strategy



Check lattice scales

- Comparison of static quark potential between $1/a = 3.6$ (β=6.351, circles) and 5.4 (β=6.638, squares) lattices:



- Result: a_1/a_2= 1.51(2)

First results

- Trial RHQ parameters for $1/a$=3.6 GeV lattice

Label	m_0	c_B	c_E	ζ
1	0.00	1.552	1.458	1.013
2	0.07	1.547	1.424	1.001
3	0.0426	1.550	1.438	1.007
4	0.0426	1.550	1.438	1.100
5	0.0426	1.550	1.438	0.900
6	0.0330	1.609	1.538	1.044
7	0.0230	1.609	1.438	1.044
8	0.0230	1.609	1.538	1.044
9	0.0426	1.609	1.438	1.044
10	0.0426	1.550	1.438	1.007
11	0.0	1.552	1.438	1.013

Label	m_0	c_B	c_E	ζ
12	0.0328	1.511	1.438	1.036
13	0.0230	1.511	1.438	1.036
14	0.0328	1.511	1.538	1.036
15	-0.01	1.700	1.574	1.022
16	0.00371	1.709	1.577	1.023
17	0.0138	1.715	1.579	1.025
18	0.02	1.719	1.580	1.026
19	0.03	1.725	1.582	1.027
20	0.08	1.707	1.576	1.023
21	0.09	1.713	1.578	1.025
22	0.1	1.719	1.580	1.026

- RHQ parameters for $1/a$ = 3.6GeV matching $1/a$ = 5.4 DWF

m_0	c_B	c_E	ζ
0.011(61)	1.73(1)	1.2(4)	1.043(7)

Outlook

- QCDOC and the $24^3 \times 64$, 3-flavor lattices will permit substantial physics achievements over the next 3-4 years.
  - K meson decays
    - $\Delta = ½$ rule
    - CP violation: ε'/ε and $\overline{K}^0$–K^0 mixing (B_K)
  - Nucleon properties
    - Charges and form factors
    - Structure functions
  - Bottom and charm physics
  - Quark matter under extreme conditions.
- We are beginning to plan the next computer:

  Perhaps 64 nodes on a chip and a petaflops scale RBRC machine by 2009?

Meson Spectrum and Kaon Physics

Chris Dawson

Meson Spectrum and Kaon Physics

Chris Dawson
RIKEN-BNL Research Center

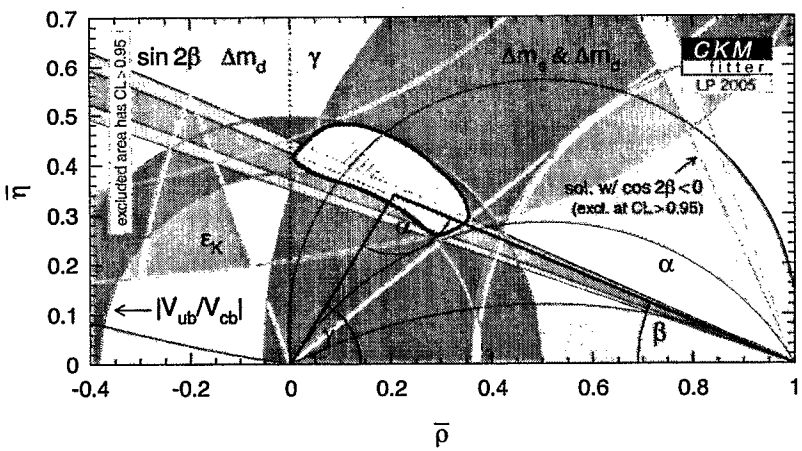
[RBC Collaboration]

B_K and the CKM

Recall:

$$|\epsilon_K| = C_\epsilon A^2 \lambda^6 \overline{\eta} \left[-\eta_1 S(x_c) + \eta_2 S(x_t)(A^2\lambda^4(1-\overline{\rho}) + \eta_3 S(x_c, x_t) \right] \hat{B}_K$$

- ▷ This is the CKMfitter group's plot from EPS 2005.



- ▷ PDG : $\hat{B}_K = 0.68 - 1.06$
- ▷ For both these results, the value quoted is the result of lattice calculations; the main error is from the use of the quenched approximation.

$N_f = 2$ Dynamical Domain Wall Fermions

Vital to move beyond the quenched approximation. A (bad) estimate of the size of these effects is the dominant error.

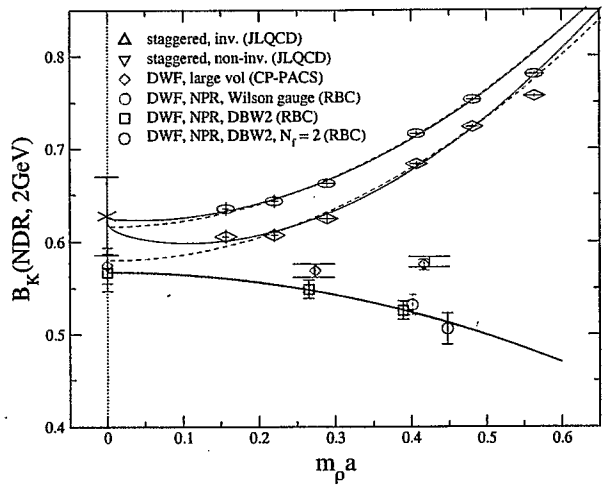
The RBC undertook a two year project using the QCDSP supercomputer to perform the first large-scale calculations using two dynamical flavours of domain wall quarks.

- ▷ three different masses: 0.02, 0.03 and 0.04 ($m_s/2 \rightarrow m_s$).
- ▷ $a^{-1} \sim 1.7\mathrm{GeV}$
- ▷ on lattices of size $16^3 \times 32$ ($\sim (2\mathrm{fm})^3 \times 4\mathrm{fm}$)
- ▷ Non-degenerate d and s quark masses.

Drawbacks:

- ▷ the "less quenched" approximation
- ▷ single lattice spacing.
- ▷ small(-ish) volume.
- ▷ relatively heavy dynamical masses.

$N_f = 2$ Dynamical Domain Wall Fermions: B_K



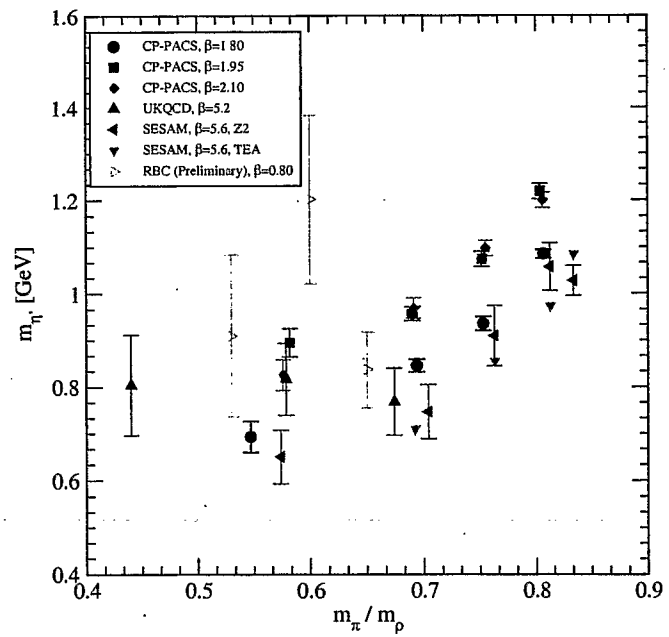
▷ Our dynamical result is only 3% lower than the quenched results closest in lattice spacing.

▷ need :

- ▷ two lattice spacings
- ▷ larger volumes
- ▷ smaller masses
- ▷ correct number of quarks

In many ways this calculation was a "warm up".

$N_f = 2$ Dynamical Domain Wall Fermions: η'



▷ Extraction still very noisy; need larger statistics on the QCDOC.

Dynamical DWF on the QCDOC

Previous results: QCDSP supercomputers based at the RBRC and Columbia.

▷ ~ 1 TFlops (peak)

The QCDOC computers: RBRC (BNL), UKQCD (Edinburgh), US Machine (BNL).

▷ each ~ 10 TFlops (peak).

Joint project UKQCD, RBC using (parts of) all three machines: 2+1 flavour Dynamical DWF

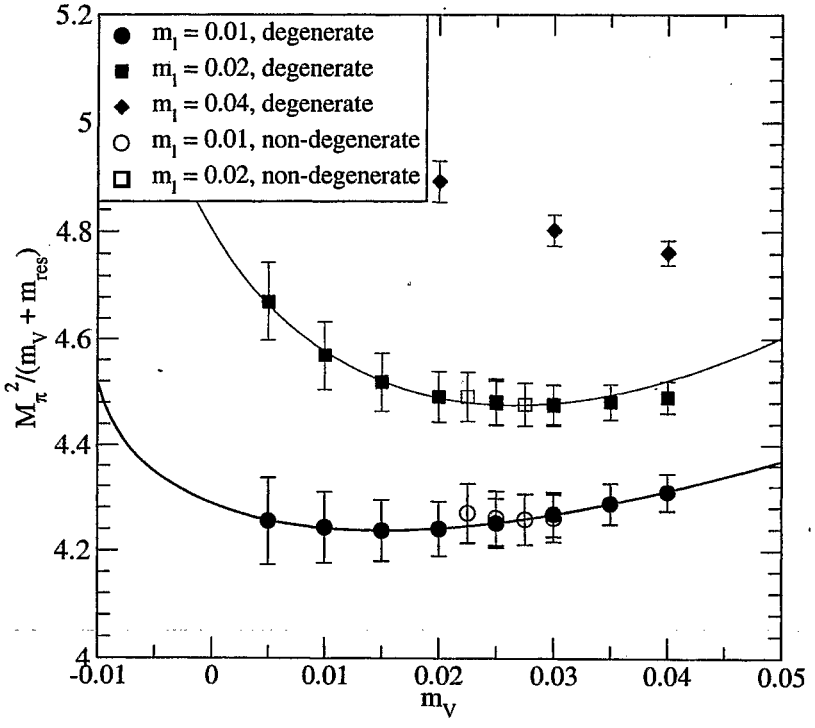
▷ larger lattice sizes ($24^3 \times 64$)

▷ lighter dynamical masses ($\rightarrow m_s/4$)

▷ (at least) two lattice spacings...

One of the first physics targets is B_K

Preliminary Results: Spectrum

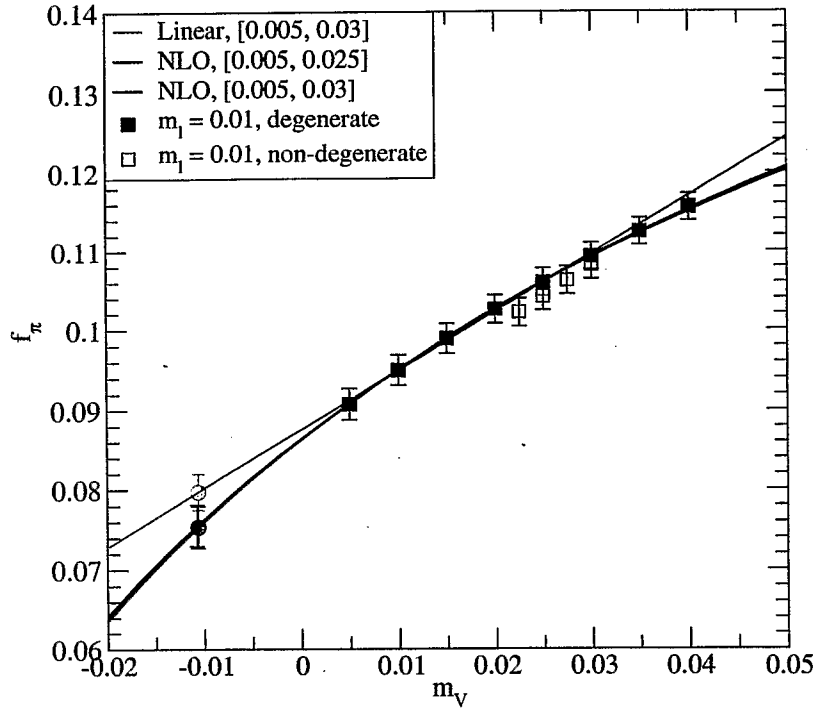


▷ This shows

$$\frac{m_{PS}}{m_1 + m_2}$$

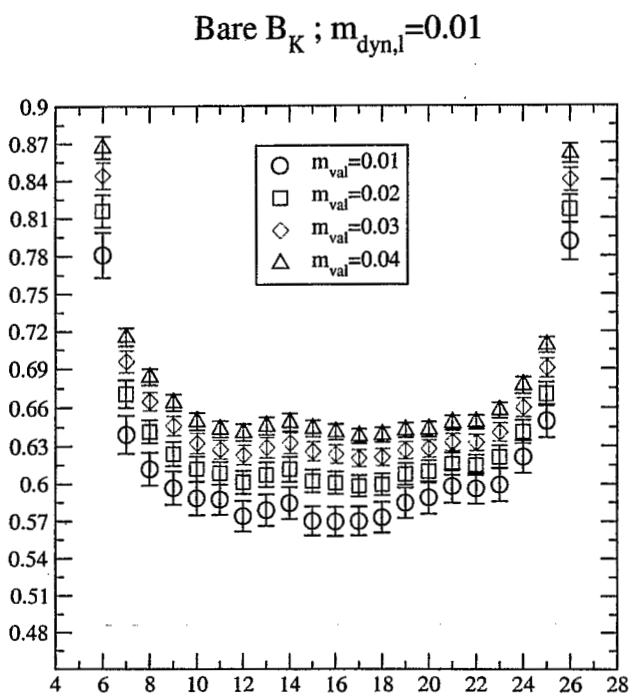
compared to the predictions of chiral perturbation theory.

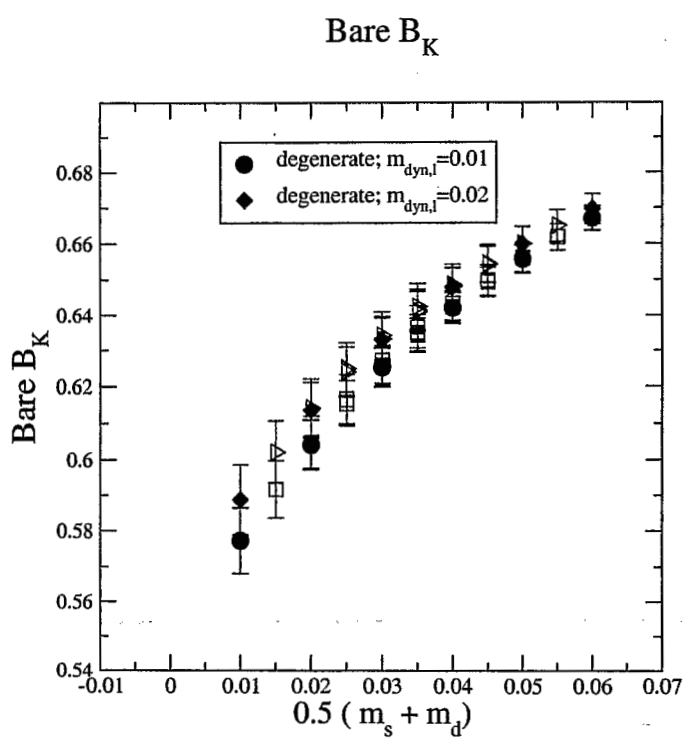
Preliminary Results: Decay Constants



▷ The pseudo-scalar decay constant, again fitted versus NLO chiral perturbation theory.

Preliminary Results: B_K





Bare numbers broadly consistent with $N_f = 2$ case:

- ▷ trend down with dynamical mass (not significant alone).
- ▷ little effect seen from non-degenerate masses.

Thermodynamics of Strongly Interacting Matter First Results from QCDOC

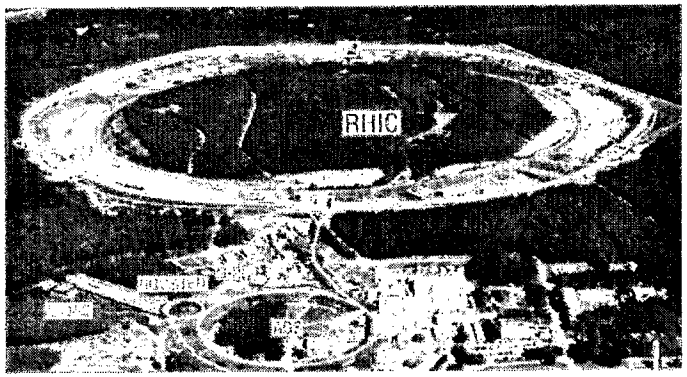
Frithjof Karsch

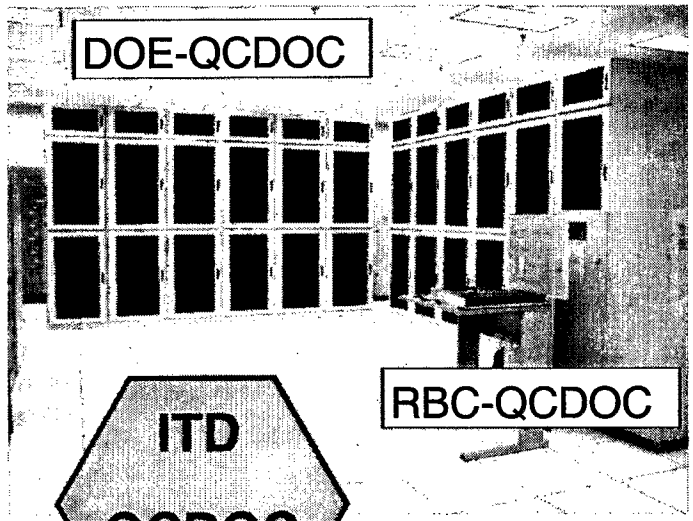
Thermodynamics of strongly interacting matter

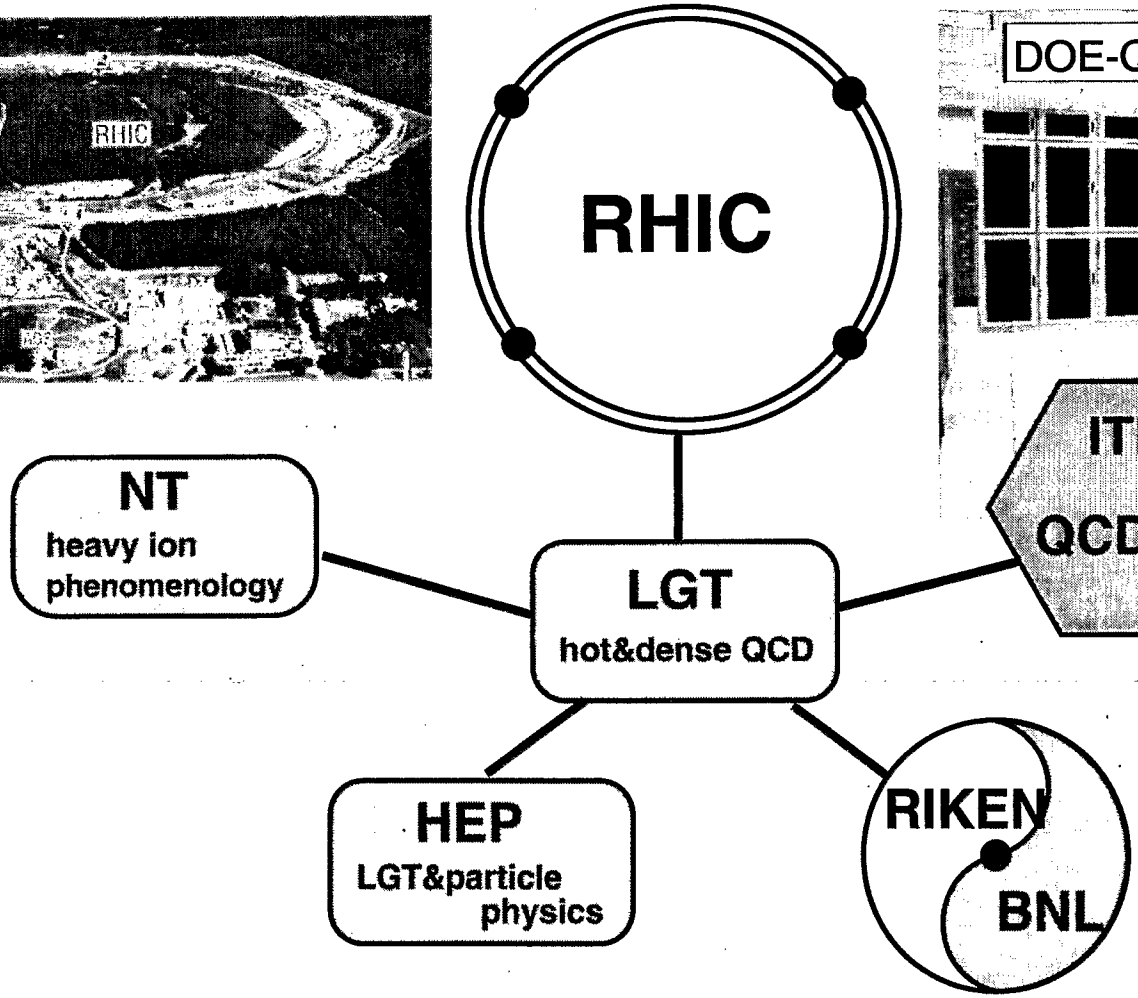
– first results from QCDOC –

- RHIC heavy ion program and LGT calculations
- The new LGT thermodynamics group at BNL
- Towards a calculation of the QCD EoS with a physical quark mass spectrum
- Conclusions

HOT Lattice Gauge Theory @ BNL

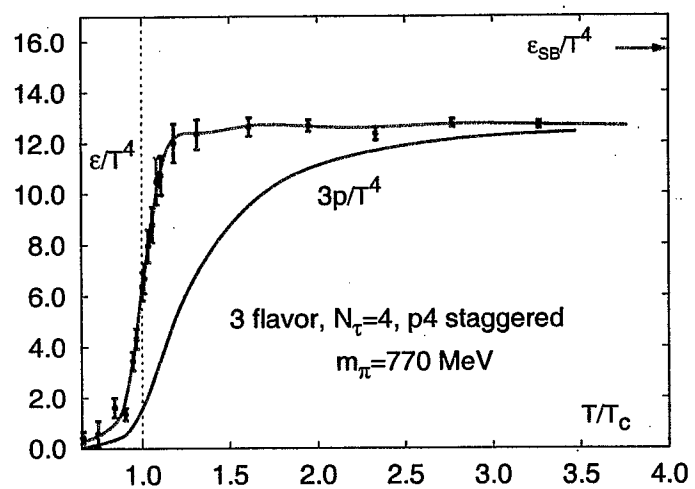


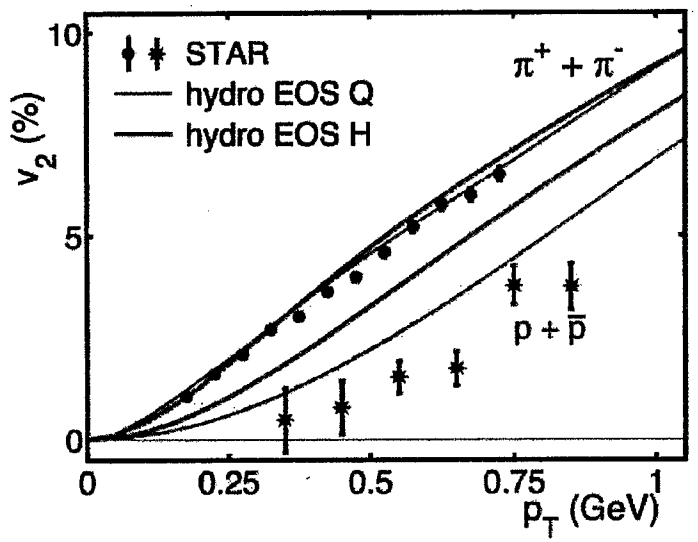




- LGT group focusing on QCD thermodynamics aims at understanding the properties of elementary particle matter under extreme conditions and thus will provide theoretical support to the experimental heavy ion program at BNL

Equation of State





state-of-the-art EoS (LGT)

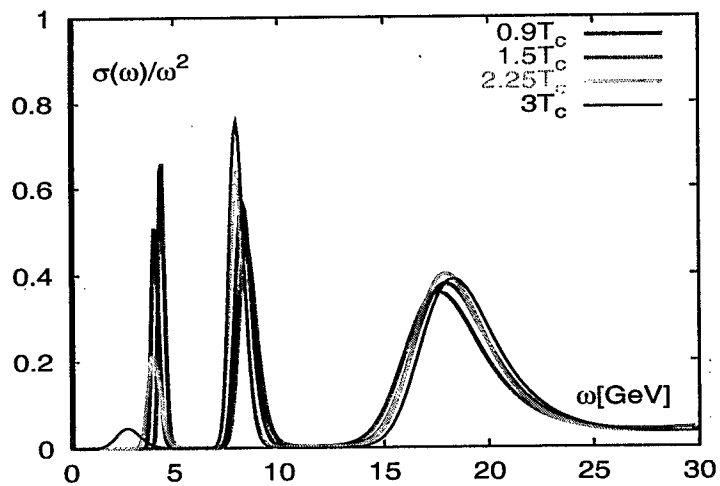
- $T_c = (173 \pm 8 \pm sys)$ MeV
  $\epsilon_c = (0.3 - 1.3)$GeV/fm^3
  - ϵ/T^4 for $m_\pi \simeq 700$ MeV; quark masses still too large

hydrodynamics, elliptic flow

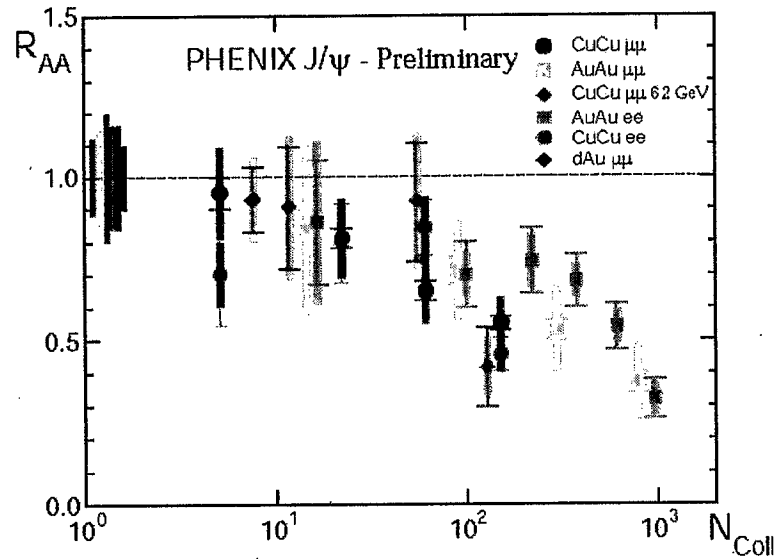
- RHIC observes large v_2; hydrodynamic description is sensitive to the QCD EoS
  - steep EoS $\Rightarrow$ small velocity of sound $\Rightarrow$ less elliptic flow

bound states or quasi-particles? – sQCD or HTL resummation?
small quark masses require huge computational effort $\Rightarrow$ QCDOC

Deconfinement and Quarkonium suppression



in-medium spectral functions



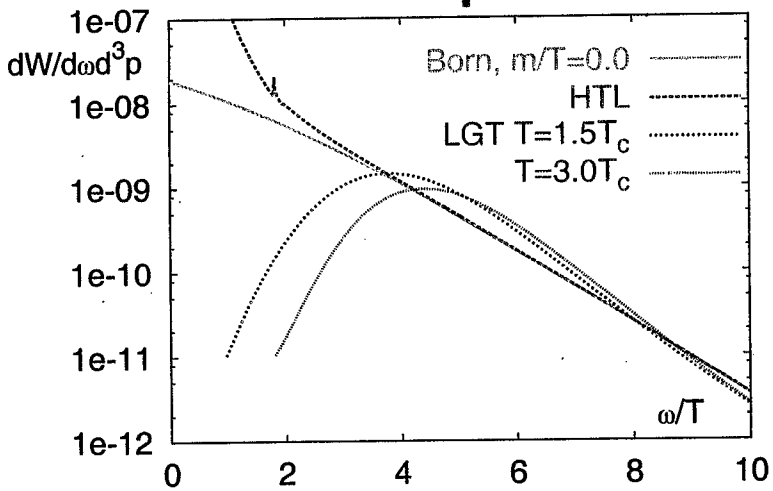
charmonium yield (RHIC)

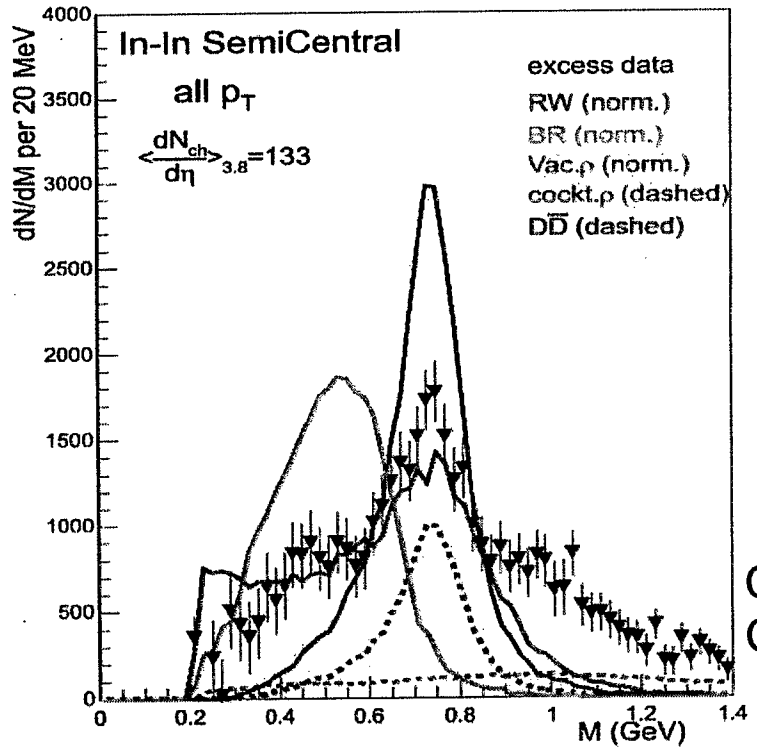
- T-dependence of spectral functions reflects dissolution of heavy quark bound states
- lattice and MEM systematics limit current predictive power

- SPS and RHIC: quarkonium yield is suppressed at high energy density
- Conversion of absorption length or N_{col} into a temperature requires knowledge of the EoS

Does the charmonium suppression at SPS turn into charmonium enhancement at RHIC ? Does it show up in the bottomonium spectrum?

Chiral symmetry and thermal dileptons





CERES, QM 200

broadening of spectral functions

- pion and rho disappear as "narrow" resonances in the QGP;
- low energy part of vector spectral functions seems to be cut off

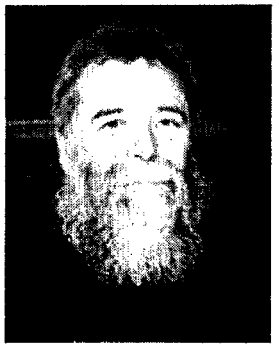
enhancement of low mass dileptons

- low mass dileptons cannot be explained by ordinary hadronic coctail;
- broadening of the rho-resonance can explain the enhancement

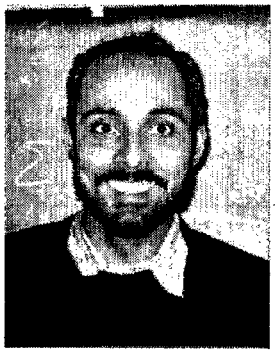
LGT and HTL-resummed calculations disagree on low energy spectrum; sQCD interprets "bump" as evidence for quasi-particle bound states

low-ω region infrared sensitive $\Rightarrow$ huge computational effort $\Rightarrow$ QCDOC

The (thermal) lattice group at BNL



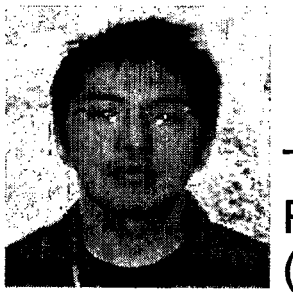
Frithjof Karsch,
group leader
(since 02/05)



Saumen Datta,
Assistant Scientist
(since 07/05)

Christian Schmidt,
Res. Associate
(since 04/05)

Peter Petreczky,
Assistant Scientist
(since 10/02)



Takashi Umeda,
Res. Associate
(since 06/05)

N.N.,
Res. Associate
(FY 2006)

The QCD-thermodynamics lattice collaboration-network

BNL/RIKEN
Tom Blum
Saumen Datta
Chris Dawson
Chulwoo Jung
Frithjof Karsch
Peter Petreczky
Kostya Petrov (⇒ NBI)
Christian Schmidt
Takashi Umeda
Felix Zantow

Tokyo
Shinji Ejiri

Columbia
Michael Cheng
Norman Christ
Robert Mawhinney

Bielefeld
Matthias Döring
Olaf Kaczmarek
Edwin Laermann
Chuan Miao
Stanislav Shcheredin
Jan van der Heide
Sönke Wissel

Current major research topics of the LGT thermodynamics group

- T_c, EoS ($\mu = 0$ and $\mu > 0$) with light dynamical quarks:
  (2+1)-flavor QCD, close to physical m_π / m_K ratio;
  exploring the continuum limit: $a \simeq (0.1 - 0.2)$ fm
  analyzing the thermodynamic limit: $V \simeq 500$ fm^3

  $\Rightarrow$ lattice sizes up to: $32^3 \times 8$; CPU-time: $\sim$ 2.5 TFlops-years (sust.)

- In-medium hadron properties, charmonium, dilepton/photon rates:
  quenched QCD on fi ne lattices ($a \simeq 0.02$ fm);
  analyzing light quark mesons with improved fermion formulations;
  exploring infra-red sensitivity of dilepton rates;
  analyzing charmonium and bottomonium spectra; colored bound state?

  $\Rightarrow$ lattice sizes up to: $128^3 \times 32$; CPU-time: $\sim$ (2-3) TFlops-years (sust.)

Status reports on the current research program

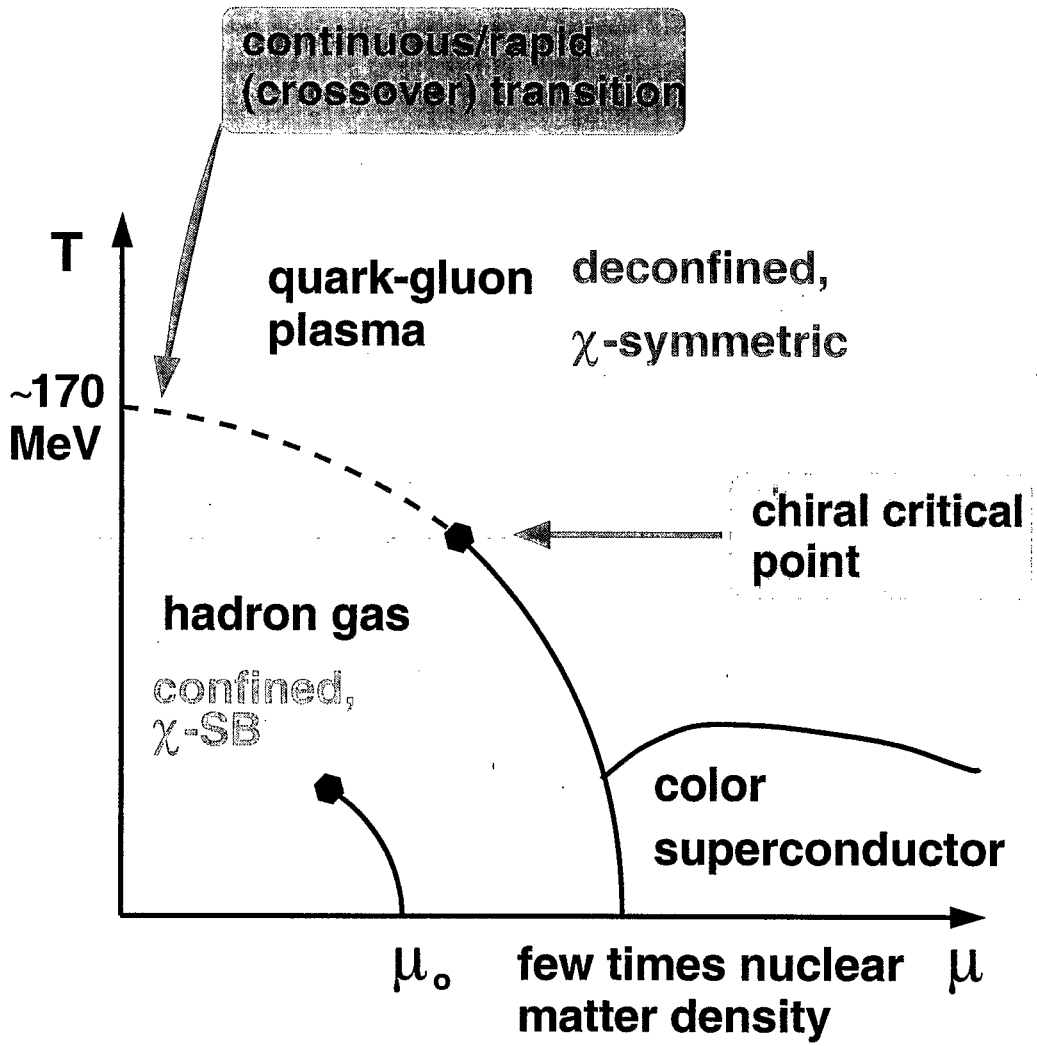
Lattice 2005, July 25-30, Dublin

- Chulwoo Jung, Thermodynamics using p4-improved staggered fermion action on QCDOC, hep-lat/0510xxx
- Michael Cheng, Scaling test of the p4-improved staggered fermion action, hep-lat/0509099
- K. Petrov, A. Jakovac, P. Petreczky and A. Velytsky, Bottomonia correlators and spectral functions at zero and fi nite temperature, hep-lat/0509138

PANIC 2005, October 24-28, Santa Fe

- Saumen Datta, Lattice results on behaviour of quarkonia in a gluonic plasma
- Christian Schmidt, QCD thermodynamics with an almost realistic quark mass spectrum
- Frithjof Karsch (plenary), Lattice QCD at high temperature and the QGP

Critical behavior in hot and dense matter: QCD phase diagram



continuous transition for small chemical potential and small quark masses at

$$T_c \simeq 170\,MeV$$
$$\epsilon_c \simeq 0.7\,GeV/fm^3$$

2nd order phase transition; Ising universality class

$T_c(\mu)$ under investigation

recent doubts on order of transition
A. Di Giacomo et al., hep-lat/0503030

location of CCP uncertain; volume dependence (Fodor/Katz)

improving accuracy on T_c is mandatory to make contact to HIC phenomenology

Thermodynamics of (2+1)-flavor QCD

The current research project on QCDOC

- determination of T_c: $N_\tau = 4,\ 6,\ 8,\ N_\sigma = 8,\ 16,\ 32$
  - explore $T = 0$ scales ($r_0,\ \sqrt{\sigma},\ m_\rho$) on $16^3 \times 32$ lattices
- calculation of the EoS: $N_\tau = 4,\ 6$
  - analyze volume dependence in the vicinity of T_c
- non-zero quark chemical potentials (Taylor expansion)
  - exploration of the phase diagram; CCP; density fluctuations
- analysis of various gluonic and hadronic screening lengths

The p4 action...

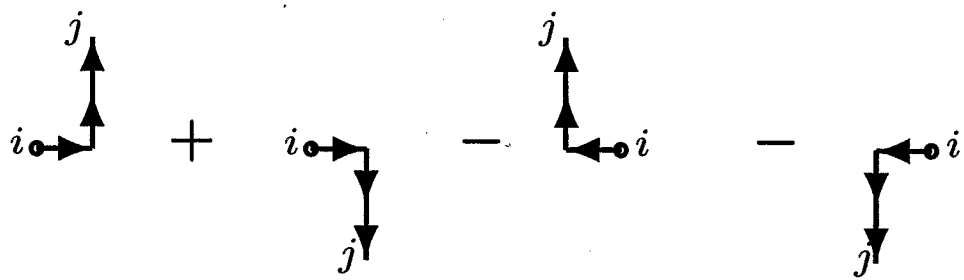
We use the 1×2 Symanzik improved gauge action

$$S_G = \beta \sum_{x,\nu>\mu} \frac{5}{3}\left(1-\frac{1}{3}\mathrm{ReTr}\,\square_{\mu\nu}(x)\right) - \frac{1}{6}\left(1-\frac{1}{6}\mathrm{ReTr}\left(\square_{\mu\nu}(x)+\square_{\mu\nu}(x)\right)\right.$$

and the p4-action fermion action $m_f\ \delta_{i\,j} + M[U]_{ij}$ with

$$M[U]_{ij} = \eta_i \left\{ \frac{3}{8}\, A[U]_{ij} \ + \frac{1}{48}\, B[U]_{ij} \right\}$$

$A[U]_{ij} =$

$B[U]_{ij} =$ 

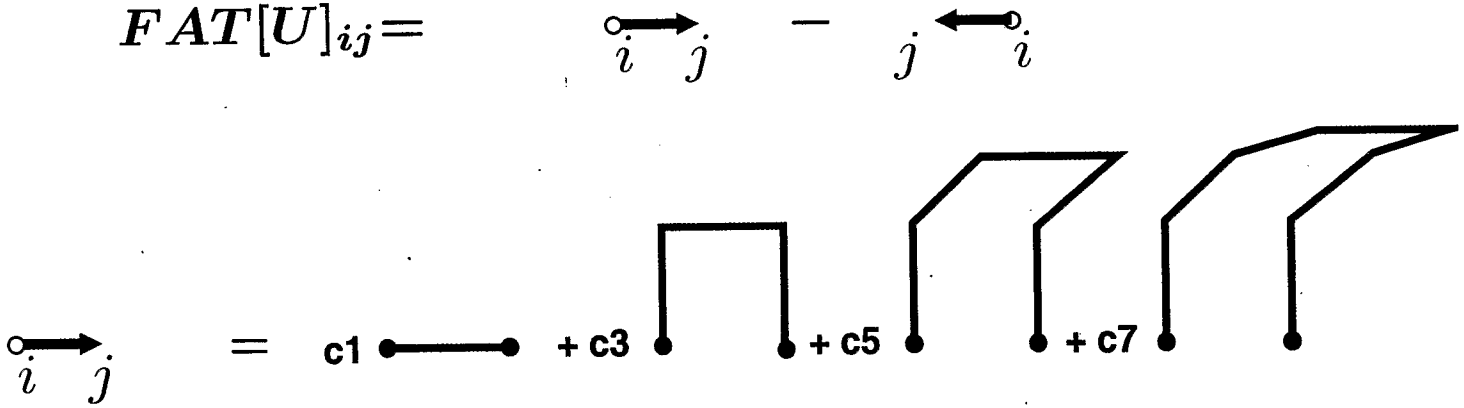
...combined with fat3/fat7 links

the 1-link term gets modifi ed

$$M[U]_{ij} = \frac{1}{2}\eta_i \left\{ FAT[U]_{i,j} - \frac{1}{4}\, A[U]_{ij} \;\; + \frac{1}{24}\, B[U]_{ij} \right\}$$

with FAT denoting MILC-FAT7

$FAT[U]_{ij} =$



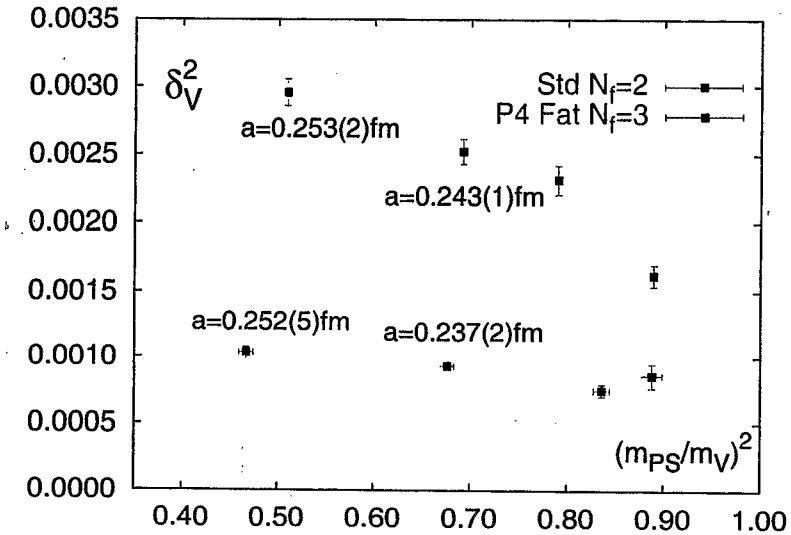
$$c1 = 1/8 \quad , \quad c3 = 1/16 \quad , \quad c5 = 1/64 \quad , \quad c7 = 1/384$$

p4fat: improved rotational and flavor symmetry

improved rotational symmetry:

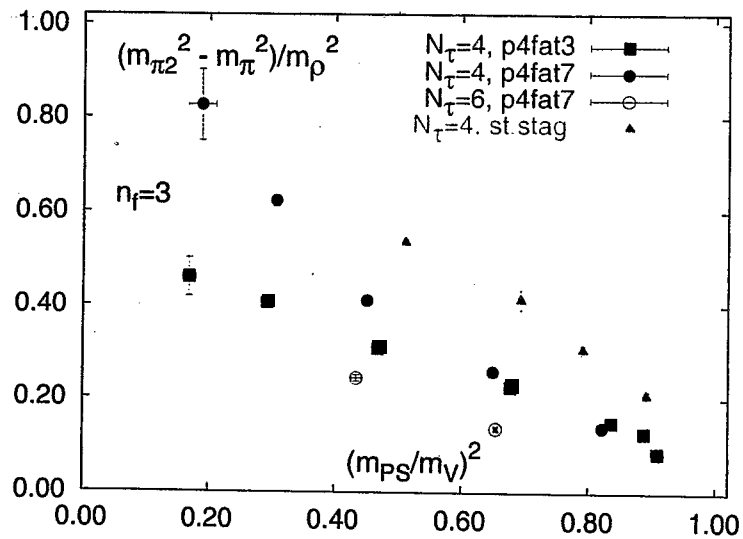
better short distance properties of heavy quark potential;

reduced cut-off dependence of bulk thermodynamics



improved flavor symmetry:

reduced mass of non-Goldstone pions



Performance of the p4fat7 program

- Performance of p4fat7 codes on QCDOC, 420Mhz, 1024 nodes, MFlops/node; optimization of parallel transport and matrix inversion
  - most runs use 4^4 or $4^3 \times 6$: they reach about 30% effi ciency; 2^4 or $2^3 \times 4$ run with about 60% of that speed

Volume	sites/node	CG(MFlops/node)	Smearing(MFlops/node)
$2^2 4^2$	64	173	271
2×4^3	128	177	293
4^4	256	207	313
$4^3 \times 6$	384	254	317
$4^2 \times 6^2$	576	264	264

- p4fat7: real time performance
  - $16^3 \times 32$, $m_{PS}/m_V \simeq 0.4$: 1024 node rack: ~ 680 traj./day

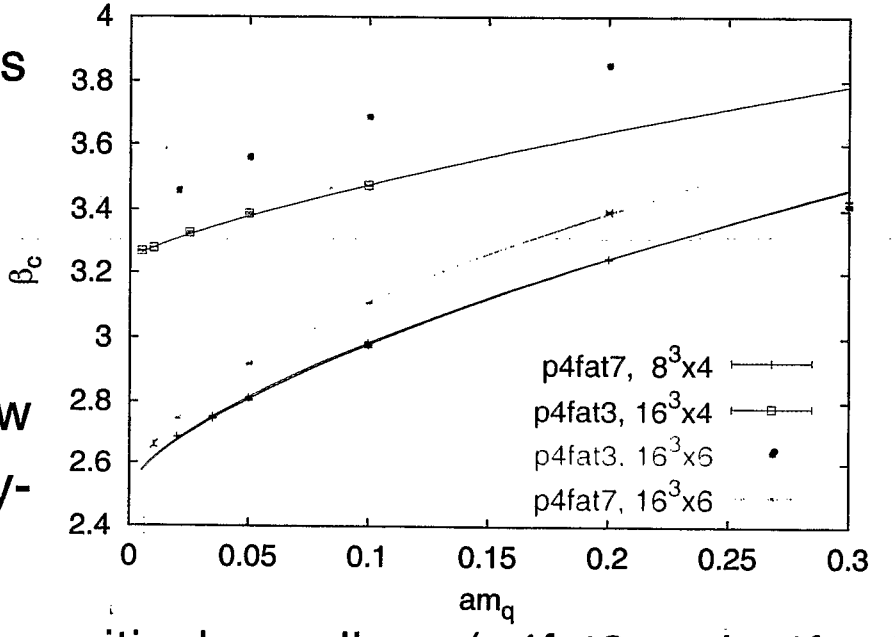
Determination of T_c (I)

goal: (2+1)-flavor QCD with a physical strange quark mass and "almost" physical light quarks ($m_\pi \simeq 200$ MeV)

1st step: 3-flavor QCD, calculation of critical couplings for several quark masses and lattice sizes ($N_\tau = 4,\ 6,\ N_\sigma = 8,\ 16,\ 32$)

364

- reached small quark masses $m_{PS}/m_V < 0.4$
- achieved high statistics up to 7000 traj. per β-value
- small β separations allow Ferrenberg-Swendsen analysis also for $N_\tau = 6$



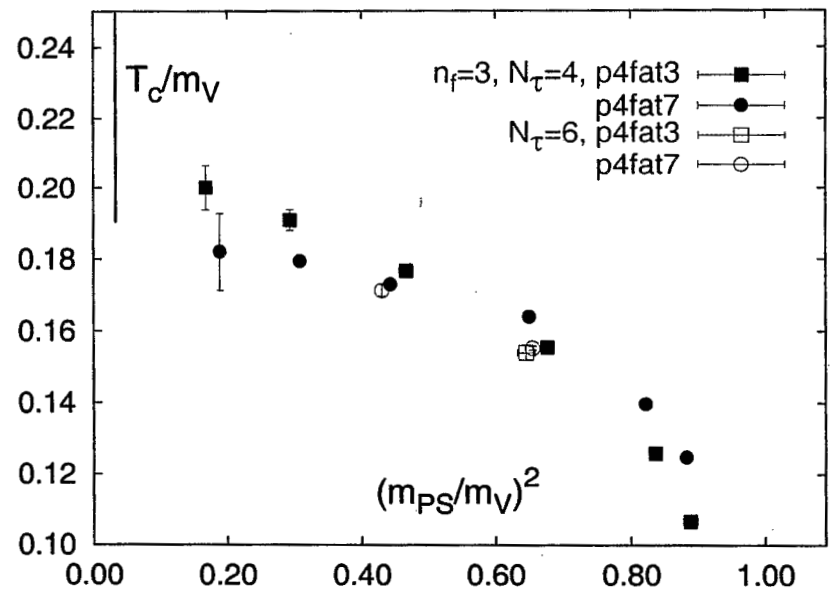
critical couplings (p4fat3 and p4fat7) from maxima of susceptibilities

Determination of T_c (II)

goal: (2+1)-flavor QCD with a physical strange quark mass and "almost" physical light quarks ($m_\pi \simeq 200$ MeV)

2nd step: determining the scale at β_c, e.g. $m_V a(\beta_c(N_\tau))$ and $1/T_c = N_\tau a(\beta_c(N_\tau)) \Rightarrow T_c/m_V = 1/(m_V a N_\tau)$

- scale determined on $16^3 \times 32$ lattices
- will check consistency of different actions
- aim at consistent picture from different scales



critical temperature from vector meson mass

Determination of T_c (III)

goal: (2+1)-flavor QCD with a physical strange quark mass and "almost" physical light quarks ($m_\pi \simeq 200$ MeV)

next steps:

a) improve scale calculations: heavy quark potential

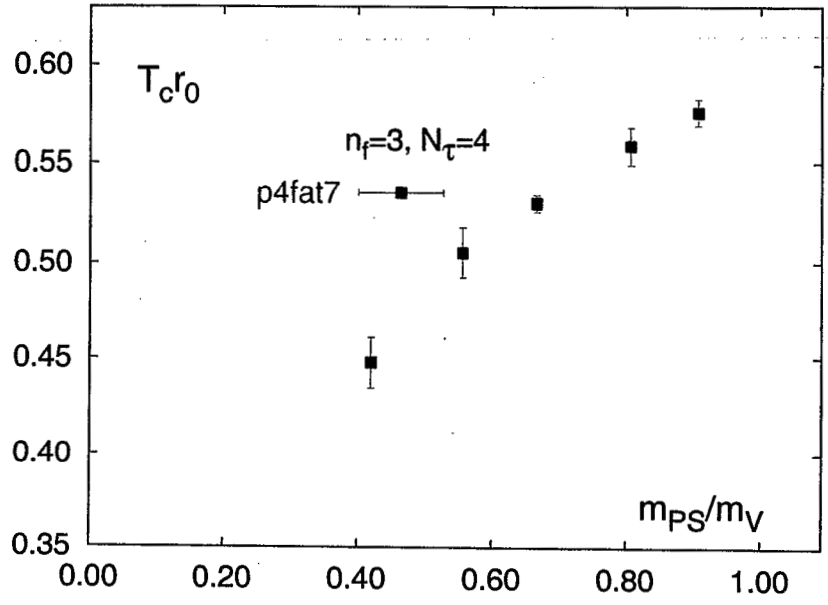
b) switch to (2+1)-flavor QCD

c) start calculation of equation of state

d) ....

...to guide your thoughts:

$T_c r_0 \simeq 2T_c\ [GeV]$



Conclusions

- The new LGT group at BNL had a perfect start:
  It is fully integrated in the RBRC/BNL environment
- The computing resources at RBRC (QCDOC) and the well established international collaborations of the group allow to perform research on QCD thermodynamics at the forefront of the fi eld
- First results on QCD thermodynamics are encouraging and will contribute to a strengthening of the theoretical background for the experimental HI-program at RHIC

Beta Decay on the Lattice

Shoichi Sasaki

RBRC Review Committee
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Beta decay on the lattice

Shoichi Sasaki (RBRC/Tokyo U.)

Semi-leptonic decays

- Kaon beta decay (K_{l3} decay) :

$$K^+ \to \pi^0 + l^+ + \nu_l \qquad K^0 \to \pi^- + l^+ + \nu_l$$

- Hyperon beta decay :

$$B' \to B + l^\pm + \nu_l(\bar{\nu}_l)$$

K_{l3} decays (1)

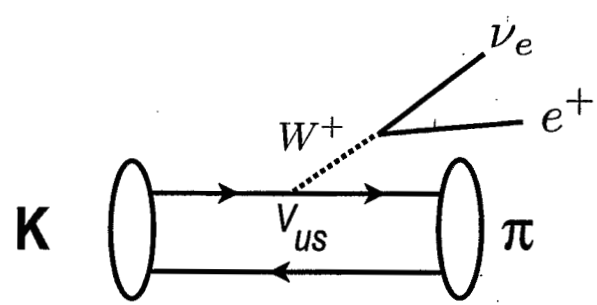
- **The 2nd simplest weak decay of Kaon**

  leptonic decay $K^+ \to \mu^+ + \nu_\mu$ F_K Kaon decay constant

  semi-leptonic decay $K^+ \to \pi^0 + l^+ + \nu_l$

- **ΔS=1 decay (s → u)**

  the best determination of the weak mixing element V_{us}



K_{l3} decays (2)

- K_{l3} decay is described by 2 form factors

$$\langle \pi(\mathbf{p}) | \bar{s}\gamma_\mu u | K(\mathbf{k}) \rangle = f_+(q^2)(k+p)_\mu + f_-(q^2)(k-p)_\mu$$

- ☑ SU(3) limit : $f_+(0) = -1, \quad f_-(0) = 0$

$$\Gamma_{\text{expt.}} \propto |f_+(0)|^2 |V_{us}|^2$$

$|V_{us}|$=0.2200(26) (PDG,2004)

- Precise evaluation of the SU(3) breaking effect on $f_+(0)$ is required for determining $|V_{us}|$

Simulations

- 2 flavors DWF + DBW2 gauge action
- Lattice cutoff: $1/a \sim 1.7$ GeV ($\beta=0.80$, $c_1=-1.4069$)
- Small residual quark mass: a few MeV ($L_5=12$, $M_5=1.8$)
- Lattice size: $V=16^3 \times 32$, $La \sim 1.9$ fm
- sea quark mass: $m_{light}=0.02$ (QCDSP) 0.03, 0.04 (QCDOC)
- valence quark mass: $3*m_{strange} \in [0.02,0.03,0.04,0.05]$
- # of statistics: each 94 measurements

K_{l3} decays (3)

- **Lattice calculation (double ratio method)**

$$C_\mu^{K\pi}(t,t') = \sum_{\mathbf{x},\mathbf{x}'} \langle O_\pi(\mathbf{x},t) V_\mu(\mathbf{x}',t') O_K^\dagger(\mathbf{0},0)\rangle$$

$$R(t,t') = \frac{C_4^{K\pi}(t,t') C_4^{\pi K}(t,t')}{C_4^{KK}(t,t') C_4^{\pi\pi}(t,t')} \longrightarrow \frac{(M_K+M_\pi)^2}{4M_K M_\pi} |f_0(q^2_{\max})|^2$$

$$f_0(q^2) \equiv f_+(q^2) + \frac{q^2}{M_K^2 - M_\pi^2} f_-(q^2) \qquad q_{\max} = M_K - M_\pi$$

In this ratio, various uncertainties, such as the statistical fluctuation, are canceled at least partially.

Preliminary results

Presented by T. Kaneko at Lattice 2005

m_{light}	$m_{strange}$	$f_+(0)$ [method1]	$f_+(0)$ [method2]
0.02	0.03	0.9984(9)	0.9988(4)
0.02	0.04	0.9944(29)	0.9951(14)
0.02	0.05	0.9887(56)	0.9893(27)

$f_+(0)$ at simulated quark mass can be determined with both systematic and statistical accuracies of < 1%.

Analysis of data at m_{light} = 0.03, 0.04 is underway.

Hyperon Beta Decay

☑ **the baryonic-version of semileptonic decay**

- *Alternative way to determine $|V_{us}|$ other than K_{l3} decays*

☑ **the SU(3)-extension of netron beta decay**

- *Axial vector form factor as well as Vector form factor (V-A int.)*
- *the SU(3) breaking effect : analysis of quark spin fractions*

$$\Delta\Sigma(= \Delta u + \Delta d + \Delta s)_{\mathrm{Expt.}} = 0.31 \pm 0.04$$

Theory: Hyperon Beta Decay

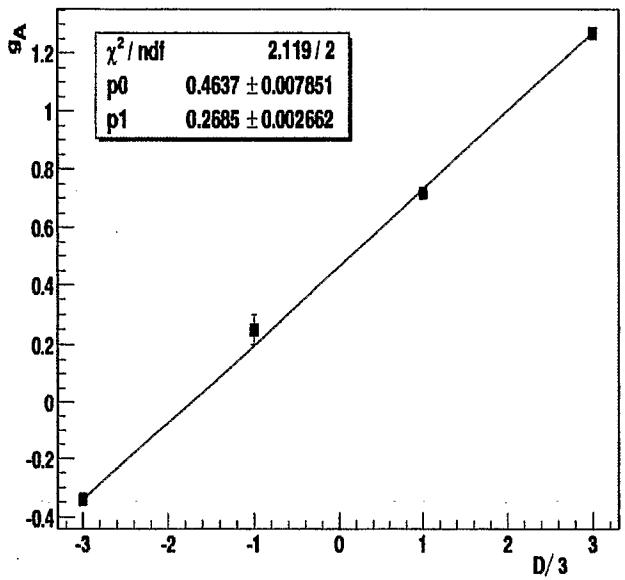
- the octet baryons ($p, n, \Lambda^0, \Sigma^{\pm,0}, \Xi^{0,-}$) admit various β-type decays

$$B' \to B + l^{\pm} + \nu_l(\bar{\nu}_l)$$

- Decays (V-A) are described in terms of 6 form factors

$$\langle B|V_\alpha - A_\alpha|B'\rangle = \bar{u}_B(p)\left[f_1(q^2)\gamma_\alpha + f_2(q^2)q_\beta\sigma_{\beta\alpha} + f_3(q^2)q_\alpha\right.$$
$$\left. + g_1(q^2)\gamma_\alpha\gamma_5 + g_2(q^2)q_\beta\sigma_{\beta\alpha}\gamma_5 + f_3(q^2)q_\alpha\gamma_5\right] u_{B'}(p')$$

Quark spin fraction ΔΣ



Assumption: SU(3) symmery

$$(g_A/g_V)_{np} = F + D = \Delta u - \Delta d$$
$$(g_A/g_V)_{\Lambda p} = F + \tfrac{1}{3}D = (2\Delta u - \Delta d - \Delta s)/3$$
$$(g_A/g_V)_{\Xi\Sigma} = F - \tfrac{1}{3}D = (\Delta u + \Delta d - 2\Delta s)/3$$
$$(g_A/g_V)_{\Sigma n} = F - D = \Delta d - \Delta s$$

$$\Delta\Sigma(= \Delta u + \Delta d + \Delta s)_{\text{Expt.}} = 0.31 \pm 0.04$$

which may have hidden systematic error stemming from unknown SU(3) breaking effects on hyperon decay

Hyperon decays on the lattice

- Preliminary results of vector form factor f_1 for $\Sigma^- \to n\, e\, \bar{\nu}_e$

  D. Becirevic et al., hep-lat/0411016

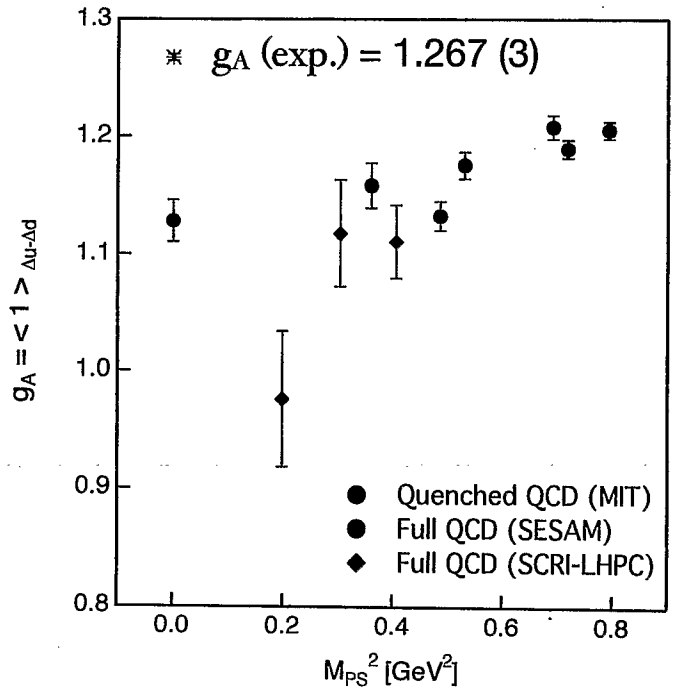
  D. Guadagnoli et al., hep-lat/0409048

  - Quenched clover, β=6.2, 24^3x56 (120 configs.)

- No results for axial form factors g_1 or g_1 / f_1
  - A long standing puzzle in the axial-vector coupling $g_A = g_1(0)$ in lattice QCD

Long-standing puzzle

$$n \longrightarrow p + e^- + \bar{\nu}_e$$



V=16³x32, β=6.0 (quenched), β=5.6 (full)
LHPC-SESAM collaboration, Phys. Rev. D66 (02) 034506

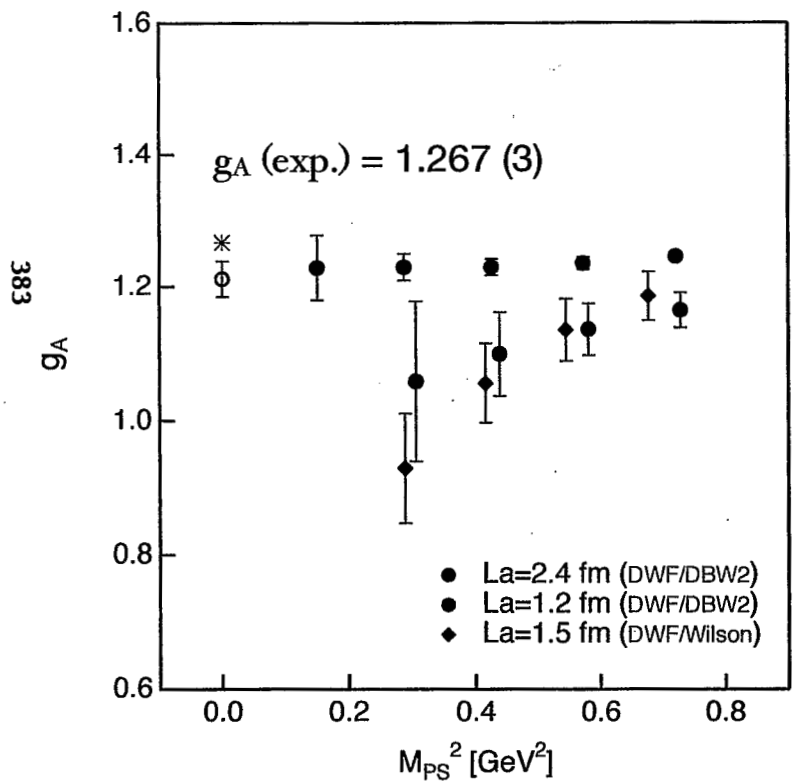
- **One of the simplest nucleon matrix elements:**
  - ✓ lowest moment
  - ✓ zero momentum transfer
  - ✓ no disconnected contribution

➡ **Lattice results always fail to reproduce experimental value**

about 20 % discrepancy

$$\langle p|(V_\mu^1 + iV_\mu^2) - (A_\mu^1 + iA_\mu^2)|n\rangle = \langle p|V_\mu^3 - A_\mu^3|p\rangle$$

Quench DWF calculation of g_A



Sasaki-Orginos-Ohta-Blum, PRD68 (03) 054509

- **Domain wall fermions**
  - ✳ excellent chiral properties

    the lightest pion mass, $M_\pi \sim 0.39$ GeV
  - ✳ especially the relation $Z_V = Z_A$
  - ✳ $(g_A/g_V)^{latt}$ directly yields the renormalized value of g_A

✓ **Clear finite volume dependence**

- a 20 % increase from 1.2 fm to 2.4 fm

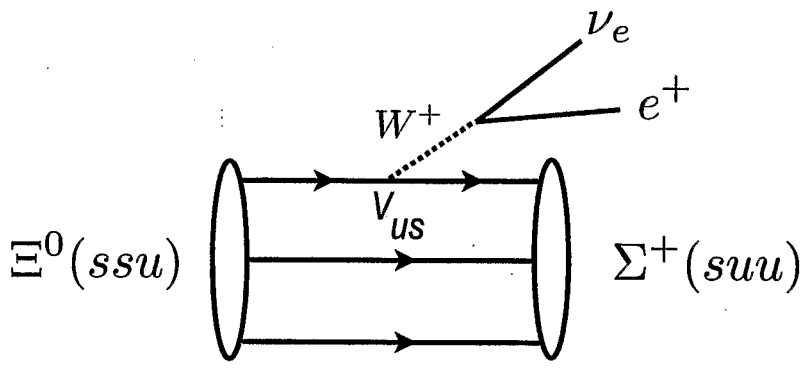
✤ **Linear extrapolation yields**

$$g_A = 1.212\ (27)$$

Hyperon Beta Decay ($\Xi^0 \rightarrow \Sigma^+$)

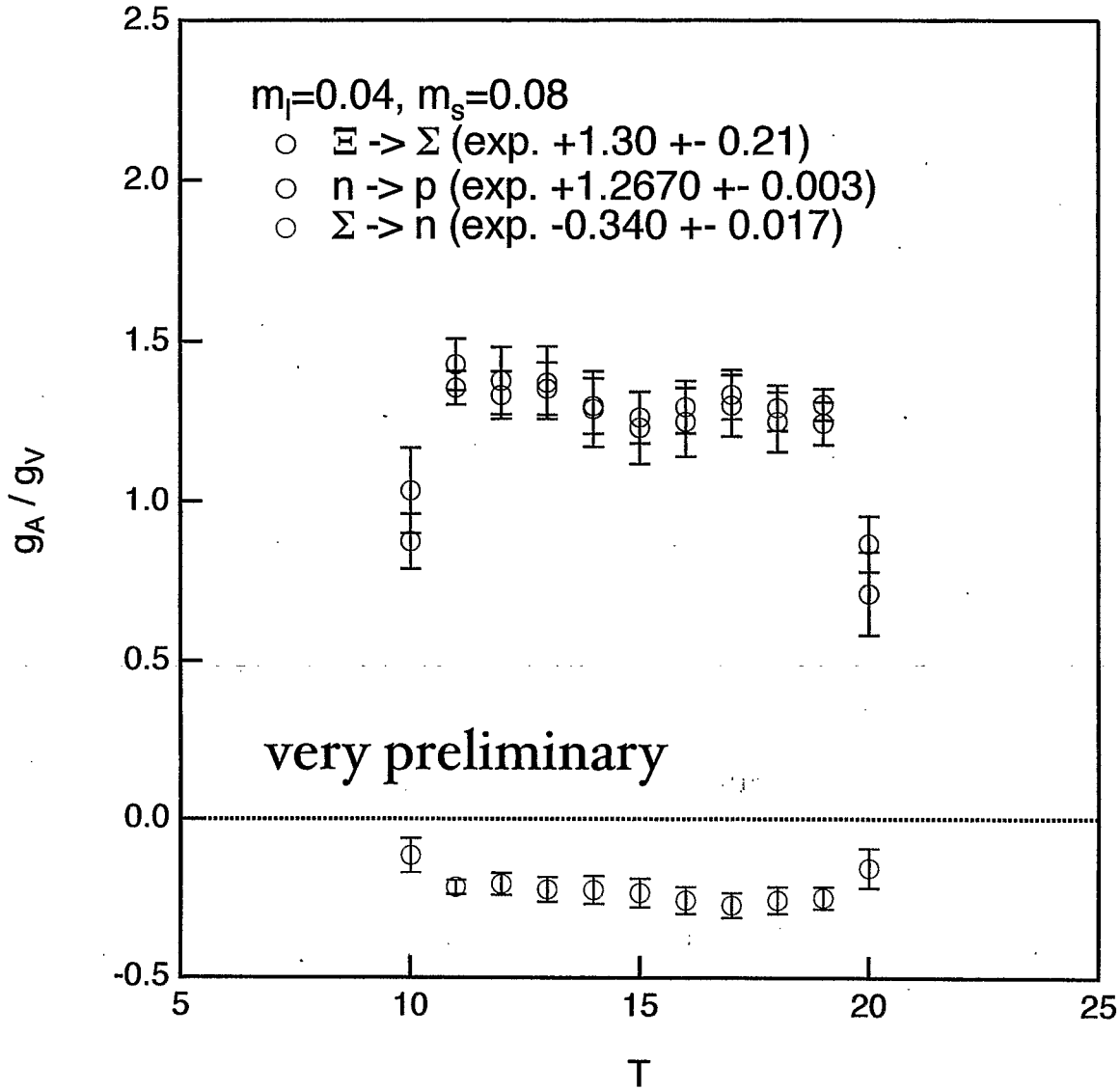
$B' \rightarrow Bl\nu$	$f_1^{SU(3)}$	g_1/f_1 (Exp.)	$(g_1/f_1)^{SU(3)}$
$n \rightarrow p$	1	1.2670 ± 0.0030	$F+D$
$\Lambda \rightarrow p$	$-\frac{\sqrt{6}}{2}$	0.718 ± 0.015	$F+\frac{1}{3}D$
$\Sigma^- \rightarrow n$	-1	-0.340 ± 0.017	$F-D$
$\Xi^- \rightarrow \Lambda$	$\frac{\sqrt{6}}{2}$	0.25 ± 0.05	$F-\frac{1}{3}D$
$\Xi^- \rightarrow \Sigma^0$	$\frac{\sqrt{2}}{2}$	N/A	$F+D$

$\Xi^0 \rightarrow \Sigma^+$ is the direct analogue of $n \rightarrow p$ under $d \leftrightarrow s$

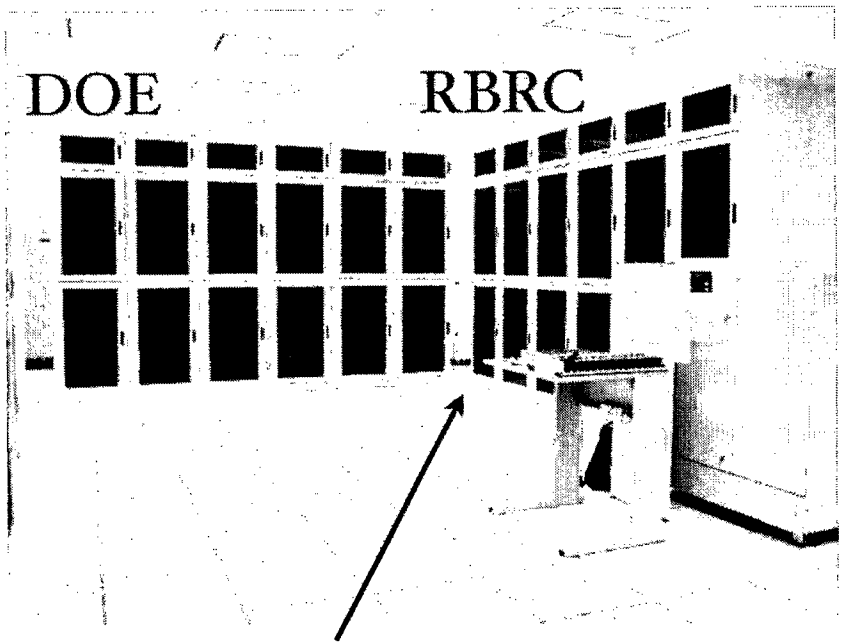


Hyperon Decay Project on QCDOC

- TEST Run on a rack of QCDOC (1024 nodes machine)
  - N_f=0, DBW2, 16^3x32x16, beta=0.87 (a^{-1}~1.3GeV),
  - m_l = 0.04, m_s = 0.08
  - # of statistics: 29
    - 3 decays: n -> p, Σ -> n, Ξ -> Σ


m_l=0.04, m_s=0.08
Ξ -> Σ (exp. +1.30 +- 0.21)
n -> p (exp. +1.2670 +- 0.003)
Σ -> n (exp. -0.340 +- 0.017)
very preliminary
g_A / g_V
T
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
5
10
15
20
25

2 + 1 flavor DWF QCD on QCDOC



RIKEN BNL Research Center Dedicates
New Supercomputer (QCDOC) for Physics Research

- DWF + Iwasaki gauge action
- Lattice cutoff: $1/a \sim 1.8$ GeV ($\beta = 2.13$, $c_1 = -0.331$)
- Lattice size: $V = 24^3 \times 64 \times 16$
  $La \sim 2.6$ fm
- $m_{light} = 3/4, 1/2, 1/4$ of $m_{strange}$
  $M_\pi \sim 250, 500, 750$ MeV

in collaboration with Columbia, UKQCD

Summary / Outlook

- ✳ RBRC lattice QCD collaboration pursues theoretical research on the SU(3) breaking effect through a first principles calculation

- ✳ The computation of weak matrix elements in lattice QCD is now progressing with steadily increasing accuracy by utilizing domain wall fermions (DWF).

- ✳ All physics program will run on QCDOC to achieve high precision calculations using 2+1 flavors of dynamical DWF quarks.

EXPERIMENTAL PRESENTATIONS

RHIC Heavy Ion Physics

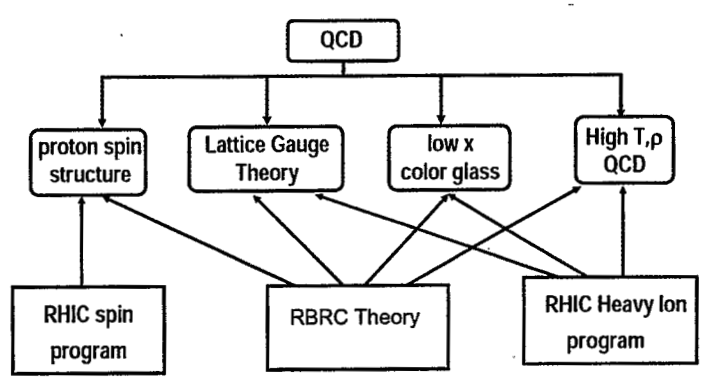
Yasuyuki Akiba

RHIC Heavy Ion Physics

Y. Akiba

Presentation
RBRC Scientific Review Committee
October 12, 2005

RBRC and RHIC: Unique QCD laboratory



RHIC: Accelerator dedicated for study of QCD (strong nuclear force)
RBRC theory: Center of QCD theory from Lattice to pQCD to Heavy Ion
RBRC and RIKEN plays leading role in both of the spin and heavy ion physics

Heavy Ion Physics at RHIC

- Create very high temperature and dense matter
  - As existed a few μ sec after the BIG BANG
  - Collide heavy nuclei to achieve maximum volume
  - 5 Runs since the start of RHIC in year 2000
    Au+Au (Run1,2,4) d+Au (Run3) Cu+Cu (Run5)
- RHIC has produced high density partonic matter
  - The four experiments of RHIC concluded in their white papers that RHIC Au+Au collisions produced very high density matter
  - The matter is strongly interacting, and it behaves like an ideal fluid (perfect liquid) – unexpected discovery.
- Next step: Detailed study of the newly discovered matter
  - How hot and dense is the medium?
  - Is thermal equilibrium achieved?
  - Is the matter de-confined?
  - What is the equation of state?

Major achievements since last SRC (Nov 2004)

The last 1 year is very productive for RHIC/PHENIX and RIKEN/RBRC group of PHENIX

- Publications
  - A large contribution from RIKEN/RBRC to PHENIX publications
- PHENIX White Paper publication
  - Summary of the first 3 years of RHIC/PHENIX operation
  - Concluded that "a new form of partonic matter is formed at RHIC
- RUN5 Cu+Cu and p+p
  - Most successful RUN of RHIC/PHENIX
    - Very high statistics Cu+Cu data
    - Very high statistics polarized proton run→First $\Delta G(x)$ measurement
- RUN4/RUN5 data analysis and QM05 conference
  - New results from PHENIX dominated the conference
    - 3 plenary talks, 20 parallel talks and >60 posters
  - A big step forward to determine the properties of the partonic matter created at RHIC

RIKEN/RBRC in PHENIX

RIKEN/RBRC personnel have important roles and positions in PHENIX, one of the two major experiment at RHIC

Deputy Spokesperson (2 out of 2)
- Y. Akiba (RIKEN)
- M. G-Perdekamp (U. Illinois/RBRC)

Executive Council Members (4 out of 13)
- Y. Akiba (RIKEN)
- M. G-Perdekamp (U. Illinois/RBRC)
- A. Deshpande (StonyBrook/RBRC)
- N. Saito (Kyoto/RIKEN)

Physics Working Group Conveners (3 out of 14)
- (M. Kaneta) (RBRC → Tohoku) (until June 2005)
- X. Wei (RBRC)
- A. Deshpande (StonyBrook/RBRC)
- K. Tanida (RIKEN) (from June 2005)

PHENIX VTX Upgrade Project
- Y. Akiba (RIKEN) project manager
- H. Ohnishi (RIKEN) pixel subsystem manager
- A. Deshpande (StonyBrook/RBRC) strip subsystem manager

Large role in PHENIX operations and data analysis
- Local Polarimeter RICH RICH-EMCAL trigger
- EMCal Muon arms

PHENIX publications

23 PRL, 9 PRC, 1 PRD, 1 PLB and 1 NPA papers published since start of RHIC
Total citations ~2200 and growing.

12 papers published since the last SRC meeting (Nov 2004)
6 papers have RIKEN/RBRC person(s) as member(s)(*) of the paper writing committee
3 papers have RIKEN/RBRC person as the chairperson(**) of the committee

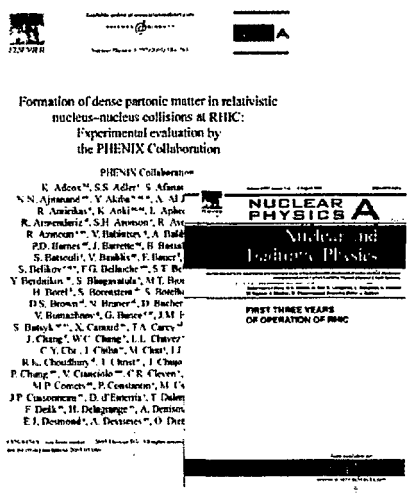
- PRL93,202002 RUN3 p+p A_{LL} (The first Spin Physics paper)(**)
- PRL94,002301 RUN2 Au+Au charm(**)
- PRL94,082302 RUN3 d+Au forward hadron
- PRC71,034908 Nch/Et(*)
- PRL94,122302 RUN2 Au+Au d/dbar
- PRD71,071102 RUN2 pp direct photon(*)
- PRC71,051902 RUN2 Au+Au baryon jet corr
- PRL94,232301 RUN2 Au+Au direct photon
- PRL94,232302 RUN1,2,4 v2 energy dependence
- NPA757,184 White paper(**)
- PRC72,014903 RUN2 phi→KK
- PRC72,024901 RUN2 Au+Au charm v2(*)

5 new papers submitted to PRL 4 papers have RIKEN/RBRC members.

- nucl-ex/0507004 RUN2 Charged particle jet correlation
- nucl-ex/0507073 RUN2 A_N for pi0 and charged hadrons (The 2nd Spin Physics result)(*)
- nucl-ex/0507032 RUN3 J/ψ production in p+p and d+Au(*)
- nucl-ex/0508034 RUN2 Open charm production in p+p via single electron(*)
- nucl-ex/0508019 RUN2 Elliptic flow of π^0 and photon(*)

PHENIX "White Paper"

- Summary of PHENIX results from RHIC Runs 1-3
  - 126 pages
  - 56 figures
  - 267 references
- Part of "First Three Years of Experiments at RHIC" special volume in Nuclear Physics A (August 8, 2005). The white papers of all 4 RHIC experiments are in the volume
- Concluded that *a new state of dense matter* formed
- PHENIX paper has already received 64 citations


Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration

NUCLEAR PHYSICS A

FIRST THREE YEARS OF OPERATION OF RHIC

Next Step: New results from RUN4/RUN5

- Conclusion of the PHENIX White Paper

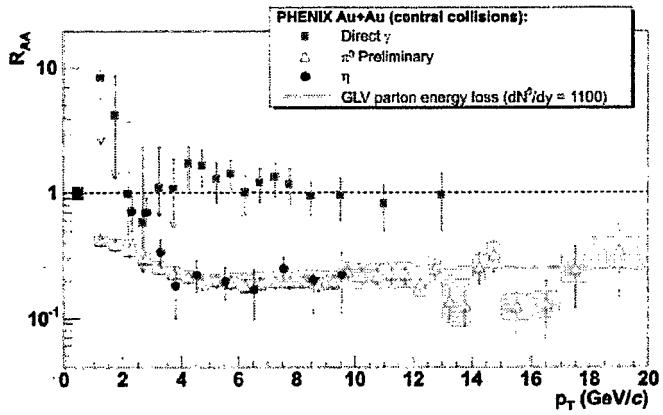
  In conclusion, there is compelling experimental evidence that heavy ion collisions at RHIC produce a state of matter characterized by very high energy densities,...

  ...additional incisive experimental measurements combined with continued refinement of the theoretical description is needed to achieve a complete understanding of the state of matter created at RHIC.

- PHENIX analyzed the high statistics (>10^9 events) data of RUN4/RUN5 to probe the properties of the dense matter formed at RHIC. The preliminary results from the analysis were presented in Quark Matter 2005 conference, the most important conference in the field in this summer.

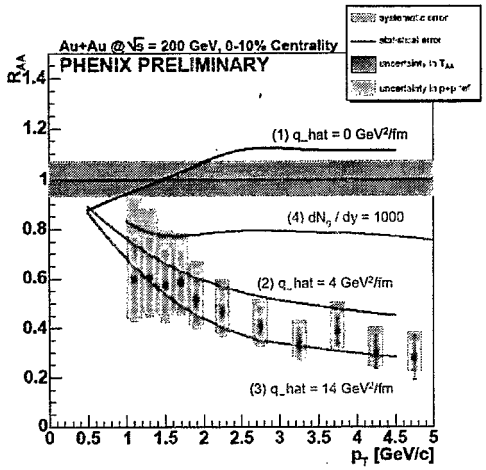
- Some of the highlights are presented in the following slides

The matter is so opaque that even a 20 GeV π^0 is stopped.



- Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c
- Common suppression for π^0 and η; it is at partonic level
- $\varepsilon > 15$ GeV/fm^3: $dN_g/dy > 1100$

The matter is so dense that even heavy quarks are stopped

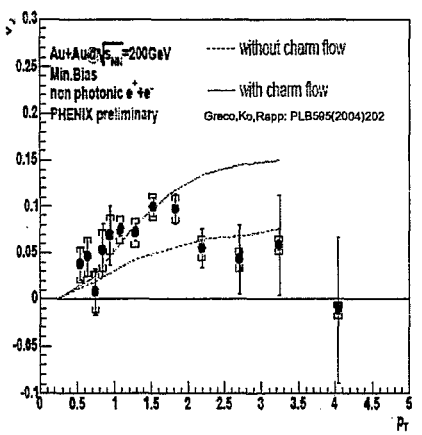


Even heavy quark (charm) suffers substantial energy loss in the matter

The data provide a strong constraint on the energy loss models.

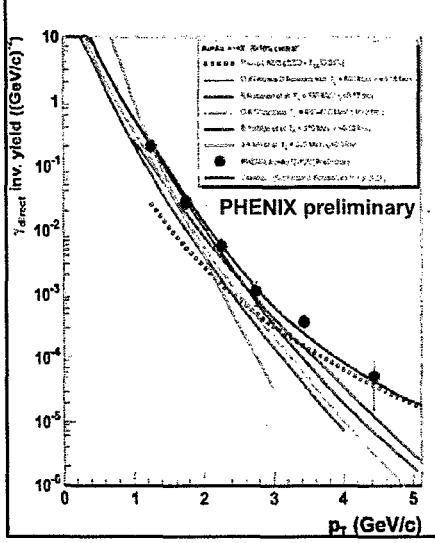
The data suggest large c-quark-medium cross section; evidence for strongly coupled QGP?

The matter is so strongly coupled that even heavy quarks flow



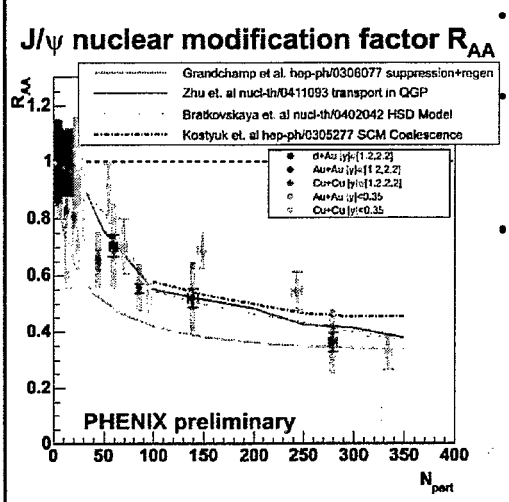
- Charm flows, but not as strong as light mesons.
- Drop of the flow strength at high p_T. Is this due to b-quark contribution?
- The data favors the model that charm quark itself flows at low p_T.
- Charm flow supports high parton density and strong coupling in the matter. It is not a weakly coupled gas.

The matter is so hot that it emits (thermal?) photon copiously



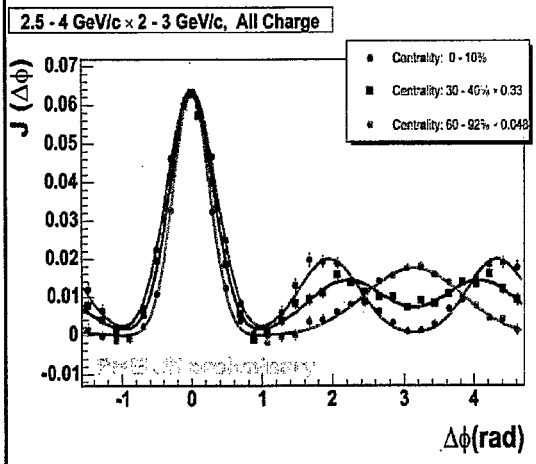
- The first promising result of direct photon measurement at low p_T from low-mass electron pair analysis.
- Are these thermal photons? The rate is above pQCD calculation. The method can be used in $p+p$ collisions.
- If it is due to thermal radiation, the data can provide the first direct measurement of the initial temperature of the matter.
- $T_0^{max} \sim$ 500-600 MeV !?
  $T_0^{ave} \sim$ 300-400 MeV !?

The matter is so dense that it melts(?) J/ψ (and regenerates it ?)



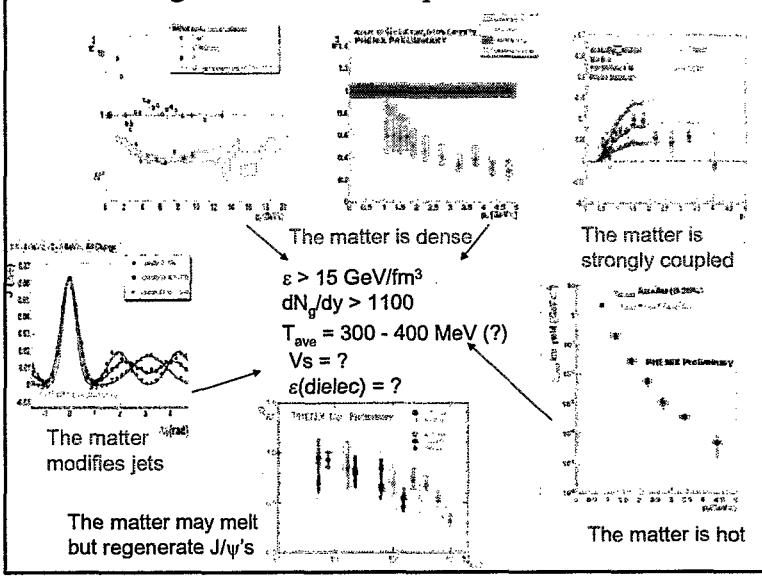
- J/ψ's are clearly suppressed beyond the cold nuclear matter effect
- The preliminary data are consistent with the predicted suppression + re-generation at the energy density of RHIC collisions.
- Can be tested by $v_2(J/\psi)$?

The matter is so dense that it modifies the shape of jets



- The shapes of jets are modified by the matter.
  - Mach cone?
  - Cerenkov?
- Can the properties of the matter be measured from the shape?
  - Sound velocity
  - Di-electric constant
- Di-jet tomography is a powerful tool to probe the matter

Probing the state of dense partonic matter



Summary

- A new form of dense matter is created in heavy ion collision at RHIC
  - Suppression of high pT particles due to matter effect
  - Large elliptic flow --- the matter behaves like a perfect liquid
- The next step of heavy ion physics at RHIC is to determine the property of the newly discovered matter
  - Importance of penetrating probes such as direct photon, heavy quarks and J/ψ.
  - Upgrade of the detector for better measurement of the matter properties and to explore the full physics opportunity
- RIKEN and RBRC plays very important role in this rapidly evolving field of phyiscs

RHIC Polarimetry

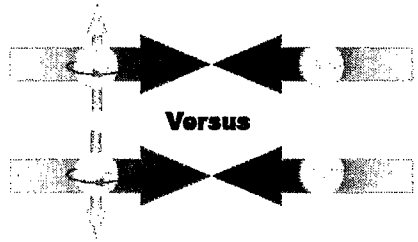
Itaru Nakagawa

RHIC Polarimetry

RIKEN / RBRC
I. Nakagawa

Polarimetry: Impact on RHIC-SPIN

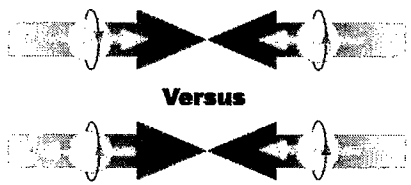
Single Spin Asymmetries



Physics Asymmetries

$$A_N = \frac{1}{P_B}\left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}\right)$$

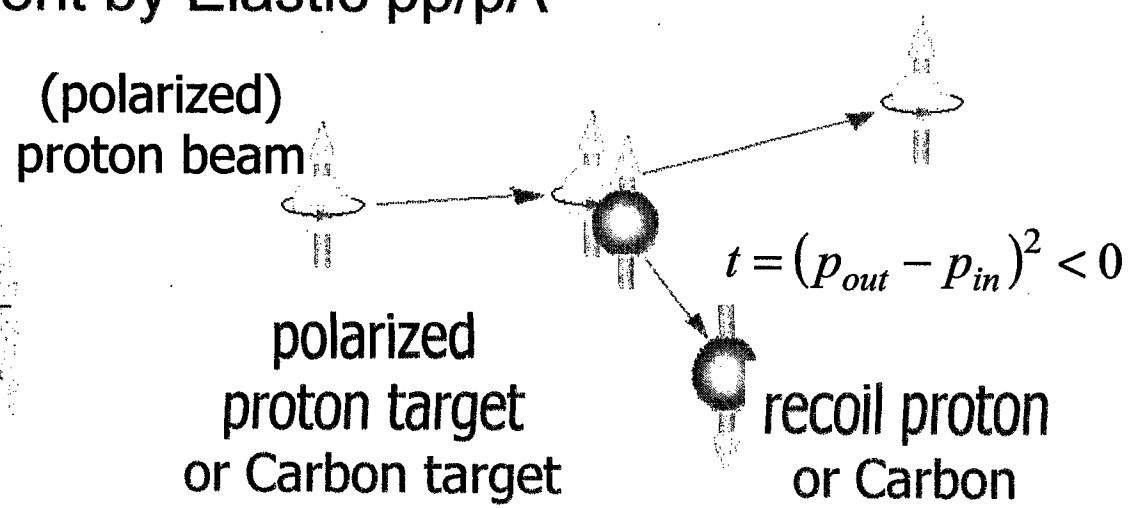
Double Spin Asymmetries



$$A_{LL} = \frac{1}{P_B^{\,2}}\left(\frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}\right) \Rightarrow \Delta G$$

Polarization measurement by Elastic pp/pA

$$P_B = -\frac{1}{A_N}\cdot\frac{N_{left} - N_{right}}{N_{left} + N_{right}}$$



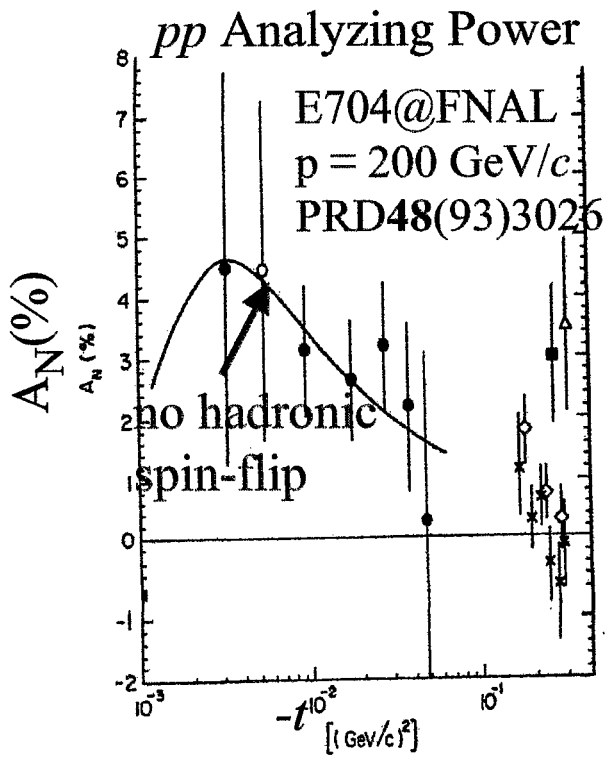
A_N at Coulomb Nuclear Interference (CNI) Region

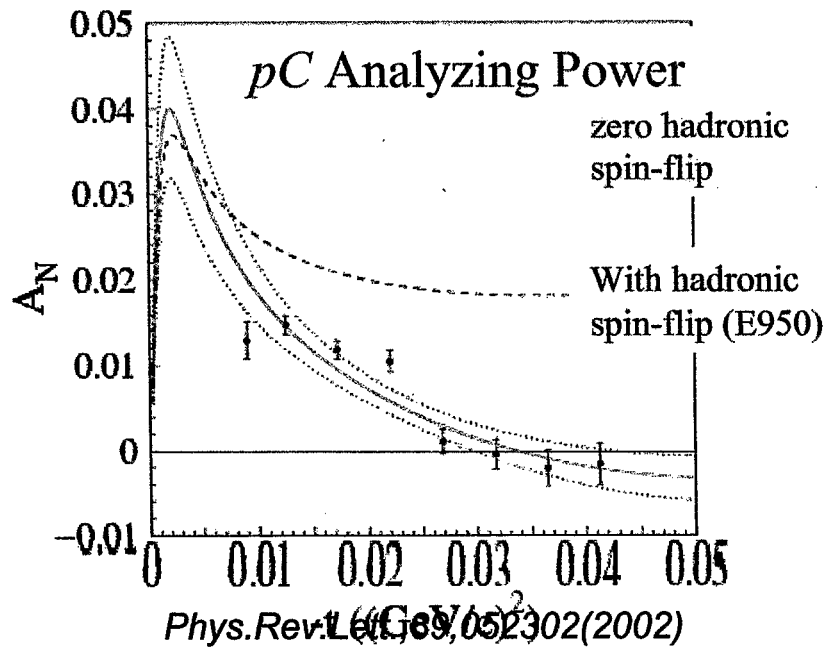
$$A_N \approx C_1 \phi^{em*}_{flip}\, \phi^{had}_{non-flip} + C_2 \phi^{em*}_{non-flip}\, \phi^{had}_{flip}$$

$\propto (\mu_p - 1)$ $\propto \sqrt{\sigma^{had}_{pp}}$ $\propto \alpha s/t$?

Regge poles
Pomeron exchange

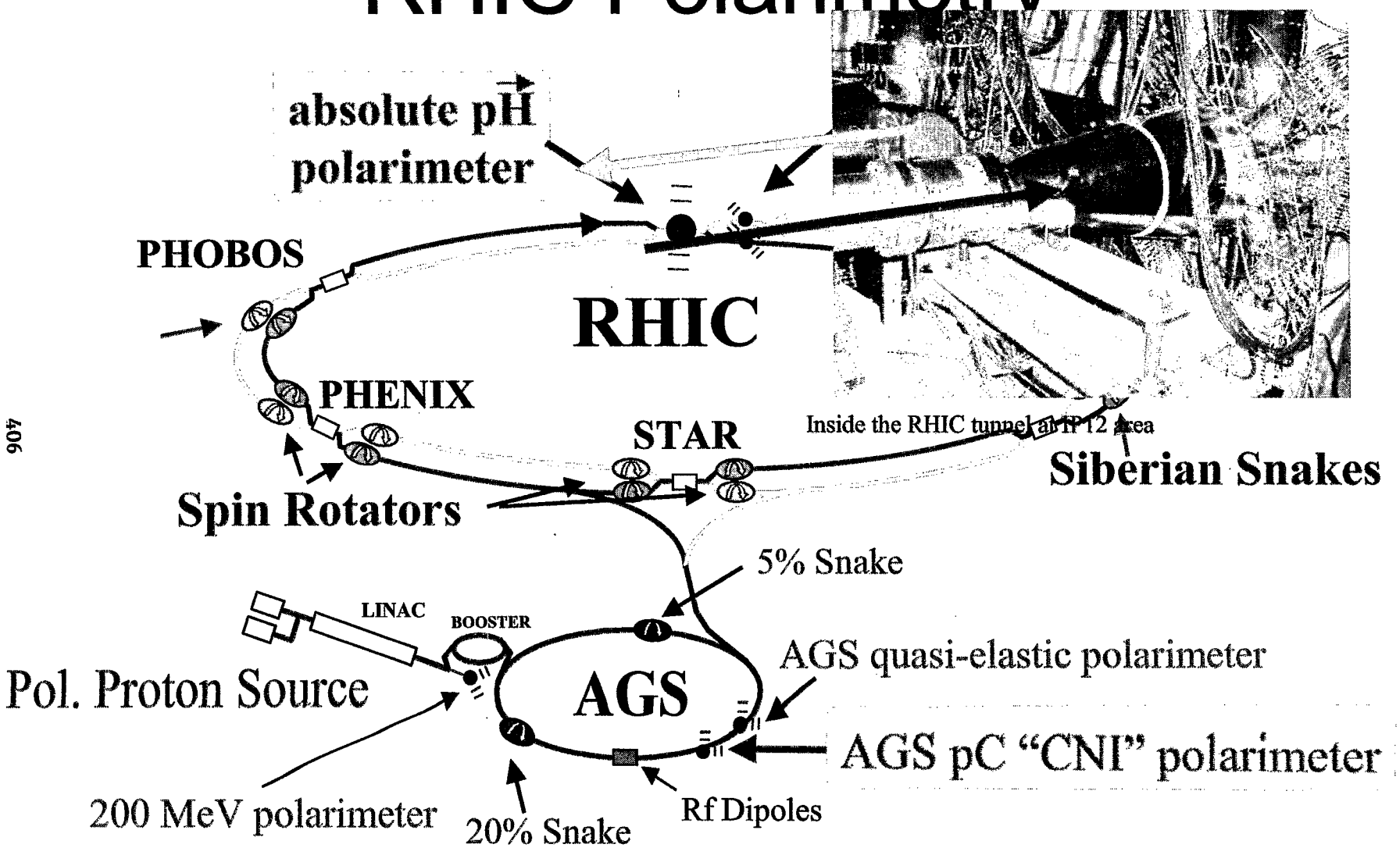
A_N is a sensitive probe of hadronic spin flip



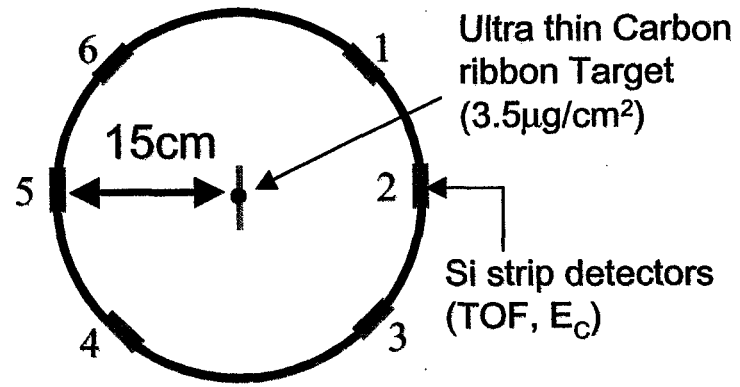


Phys.Rev.Lett.89,052302(2002)

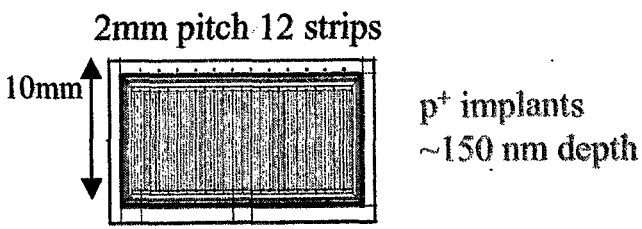
RHIC Polarimetry



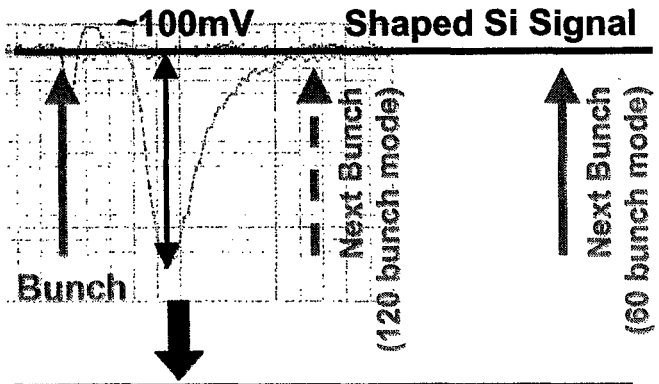
pC Detector Setup



Thin dead layer for low energy carbon spectroscopy



72 strips in total



Wave Form Digitizer (WFD)

420 Msamples/sec

- Pulse Height
- TOF
- TMAX
- Bunch ID
- Integral (Q)
- revolution #

online

Select carbons at on-board LUT

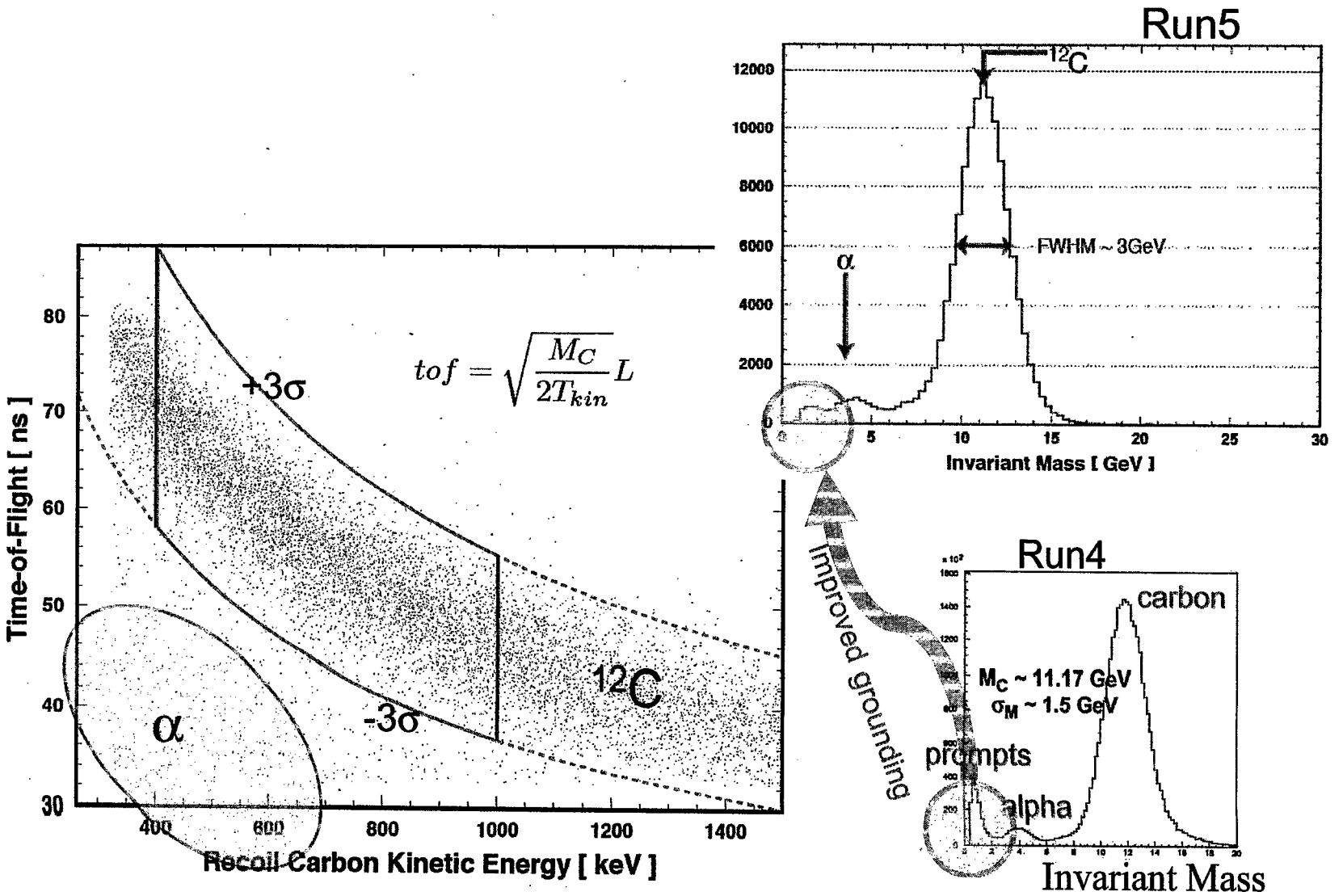
- Scaler data
- Asymmetry calculation
- Online results (to experiments)

offline

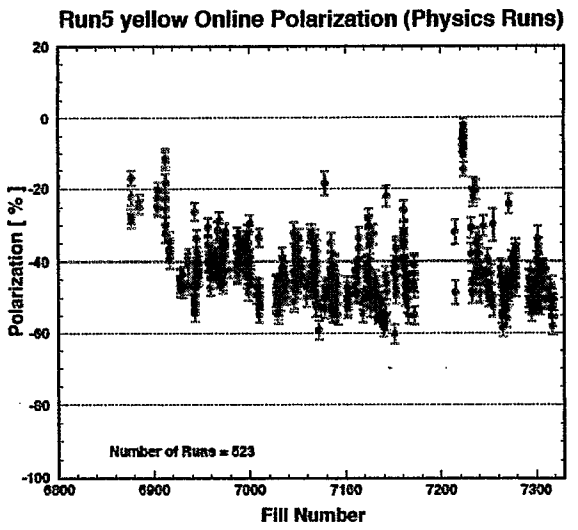
Event by event data

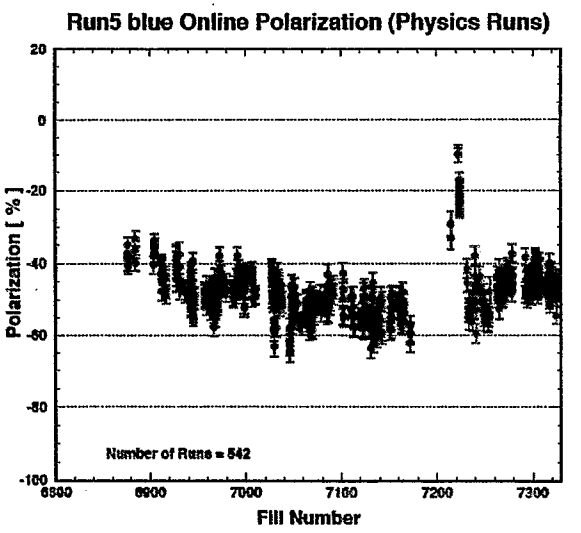
- Stored in on-board memory
- Used for offline detailed study

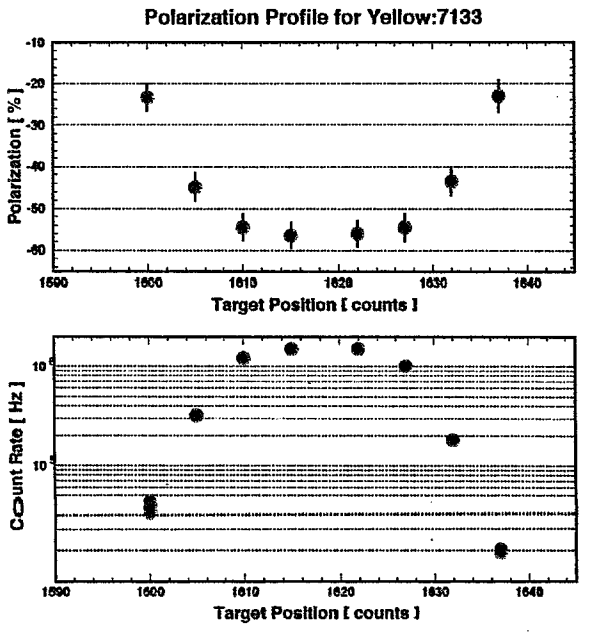
Event Selection

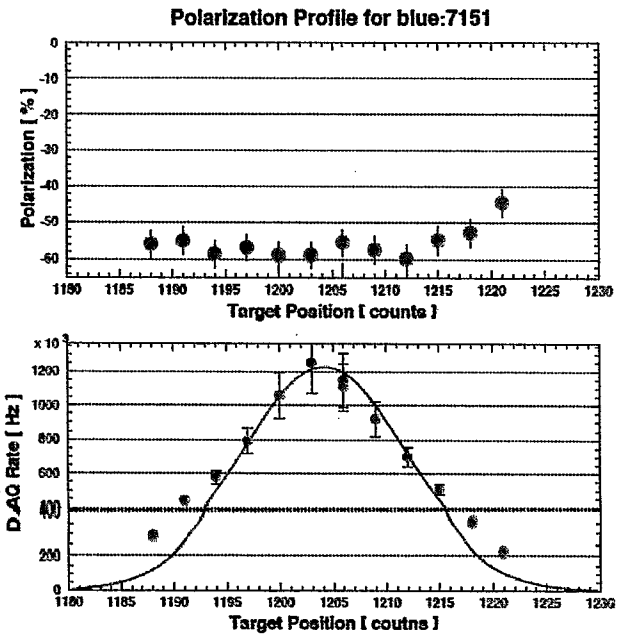


Run05 Online Results

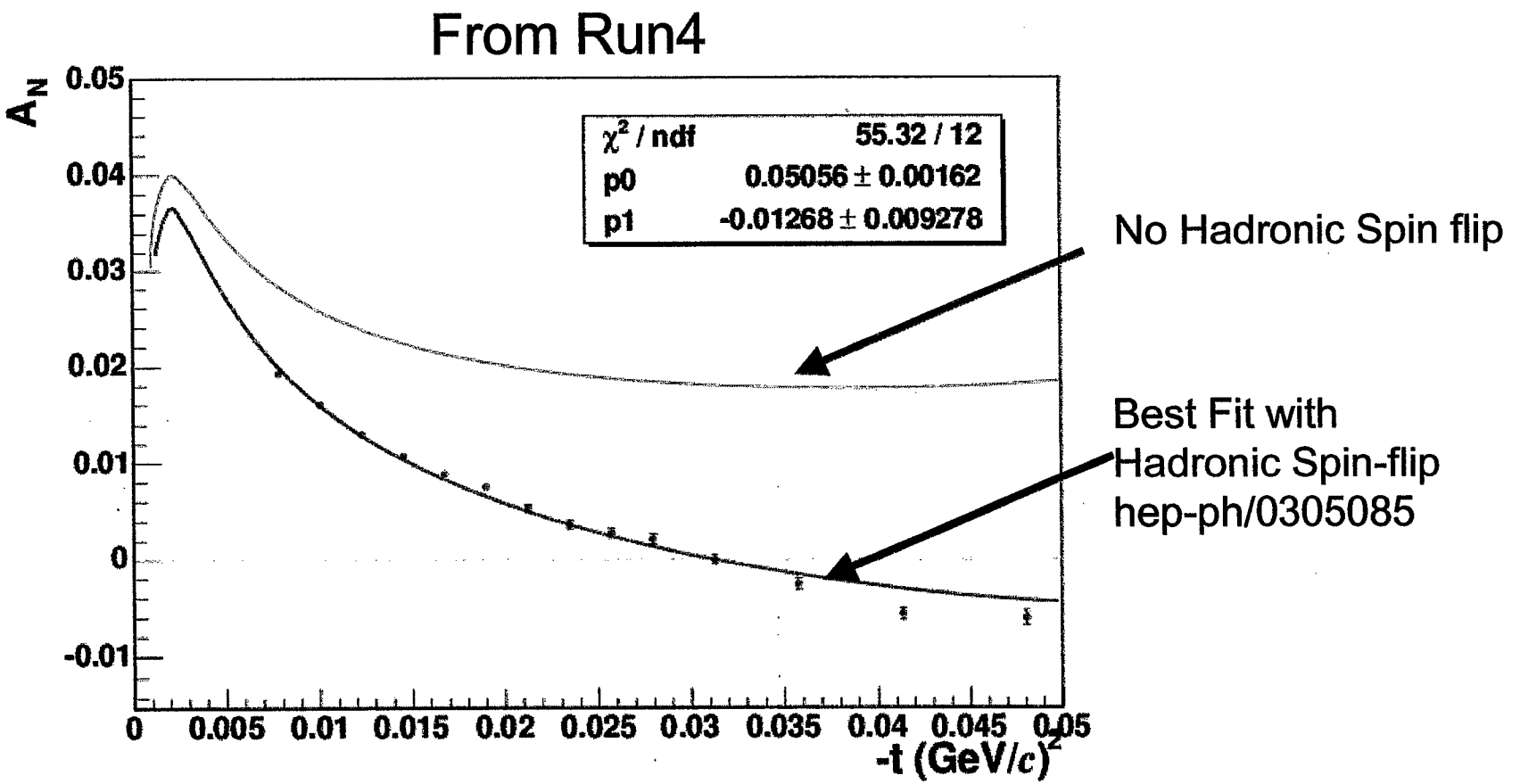






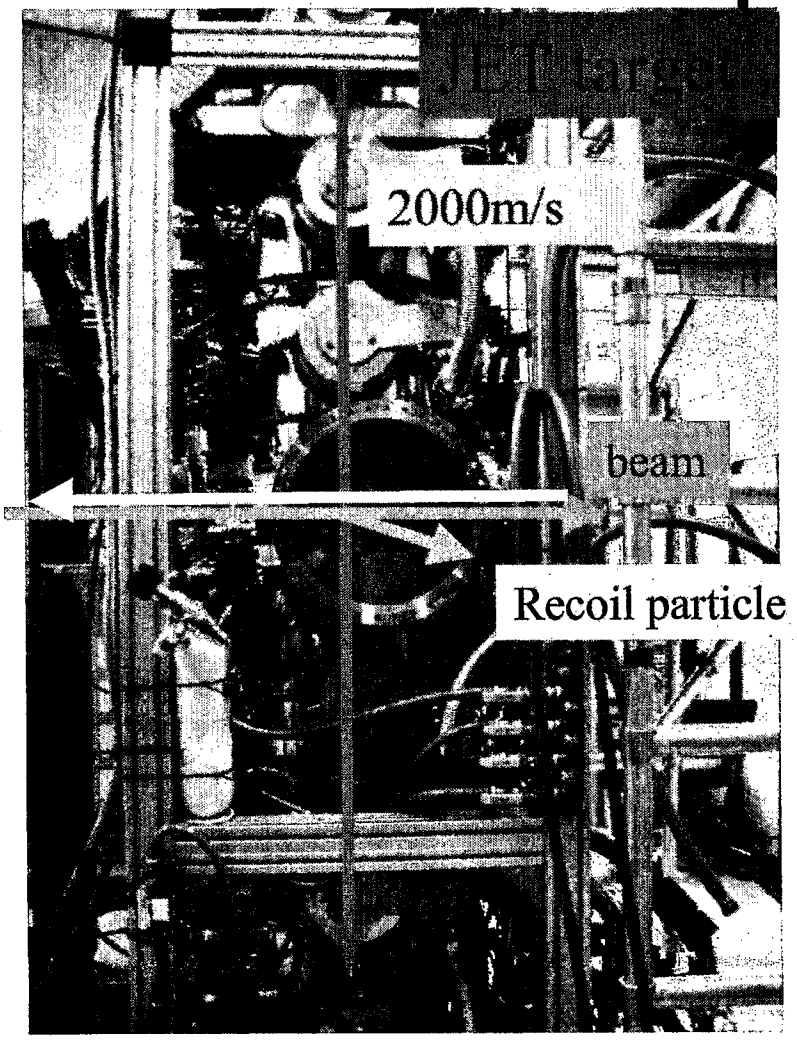


pC extended t-range A_N

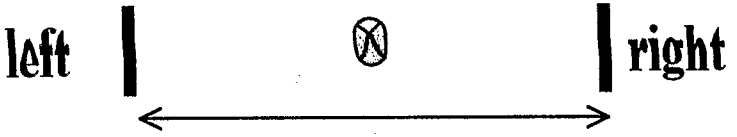


pp elastic (Jet Target)

Run05 Setup



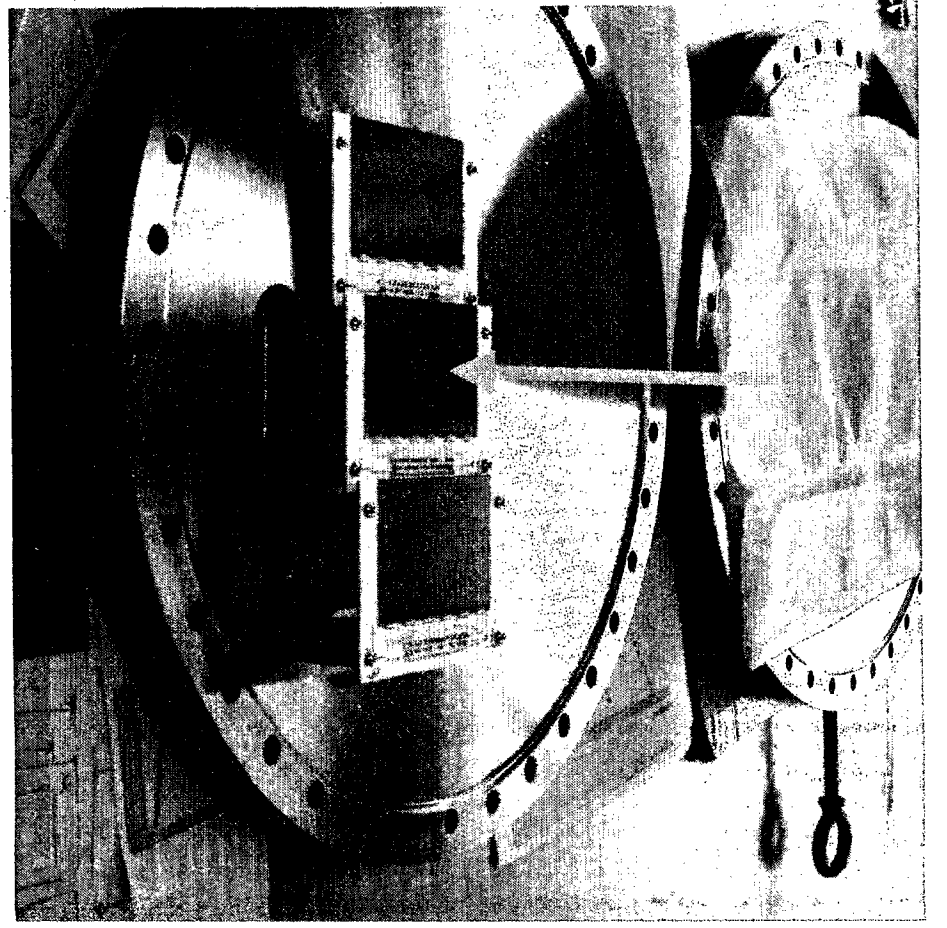
Left-right pairs



Si detectors (8cm * 5cm)*3*2sides

1ch width = 4mm (400strips)

Strip runs vertical with beam



Recoil Si Spectrometer

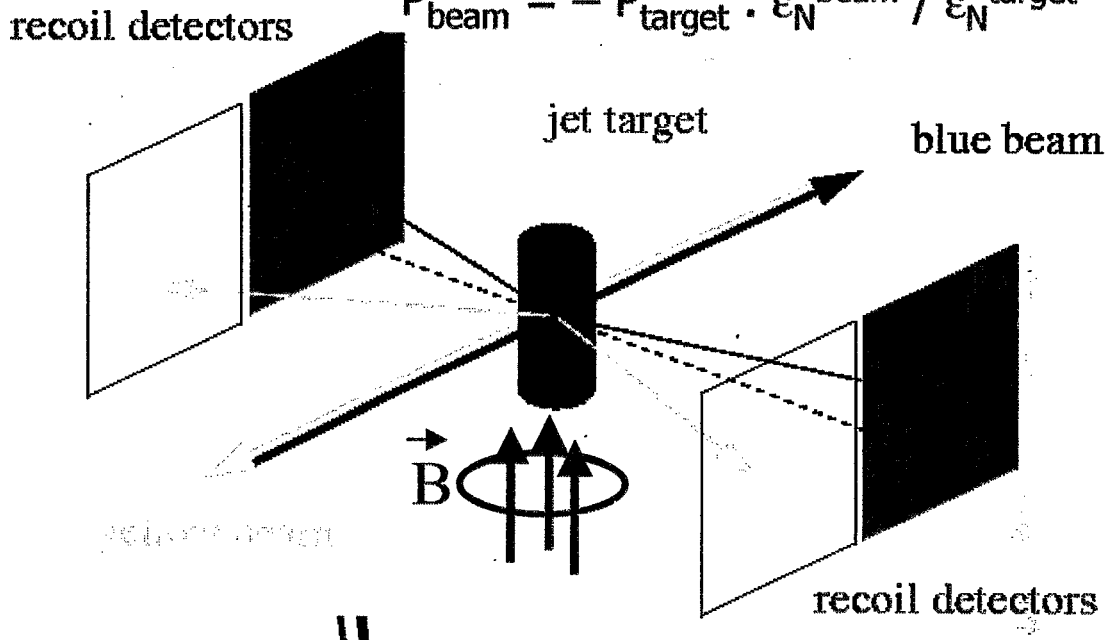
$A_N^{beam}(t) = -A_N^{target}(t)$

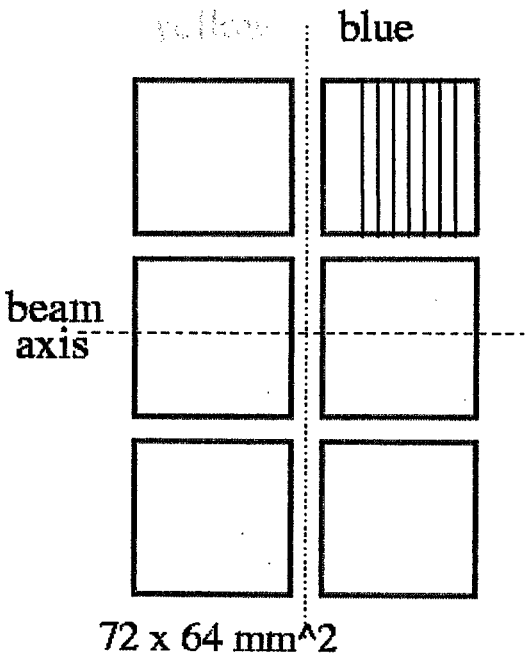
for elastic scattering only!

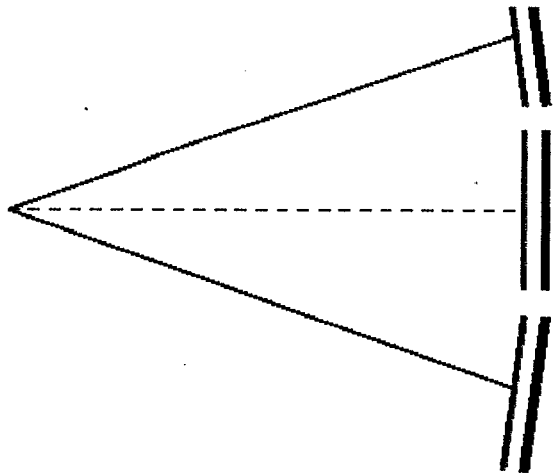
$P_{beam} = -P_{target} \cdot \varepsilon_N^{beam} / \varepsilon_N^{target}$

6 Si detectors covering the blue beam =>
MEASURE
- energy (res. < 50 keV)
- time of flight (res. < 2 ns)
- scattering angle (res. ~ 5 mrad)

of recoil protons from
$pp \rightarrow pp$ elastic scattering



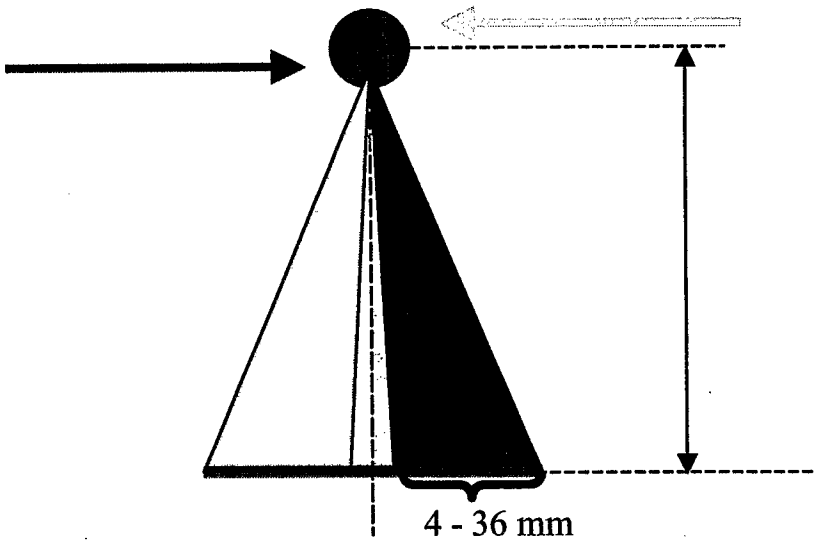


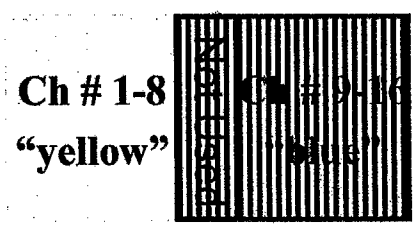


HAVE "design" azimuthal coverage

one Si layer only
⇒ smaller energy range
⇒ reduced bkg rejection power

What's New Run05

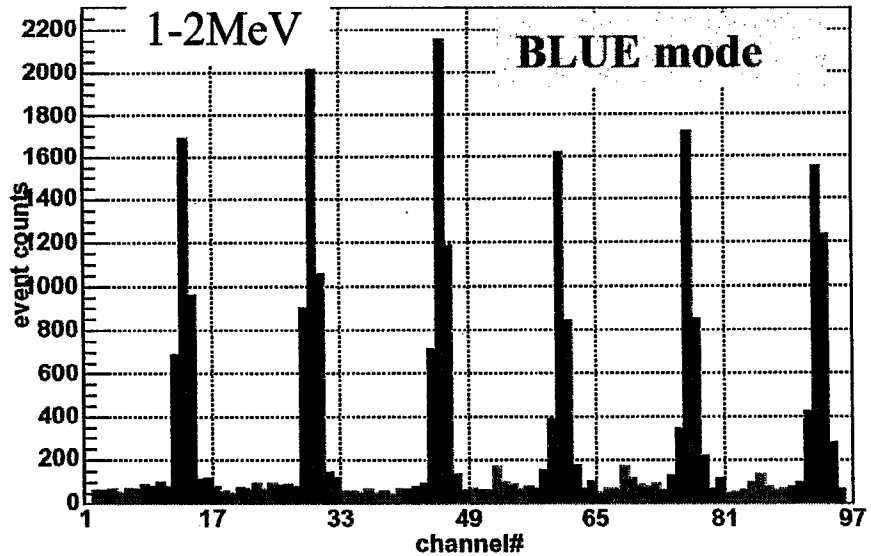


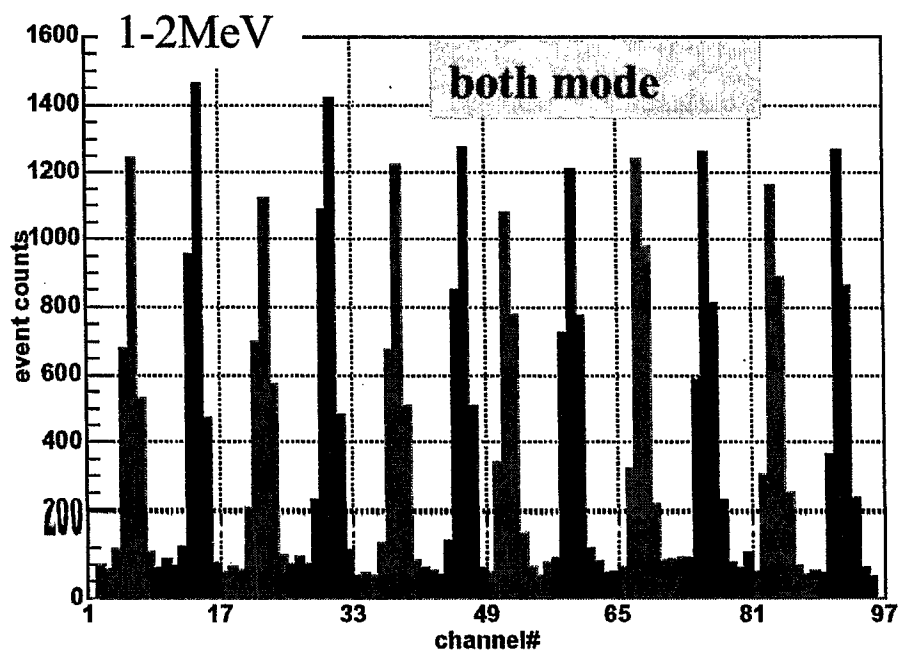


Sequential / Simultaneous measurement of blue & yellow

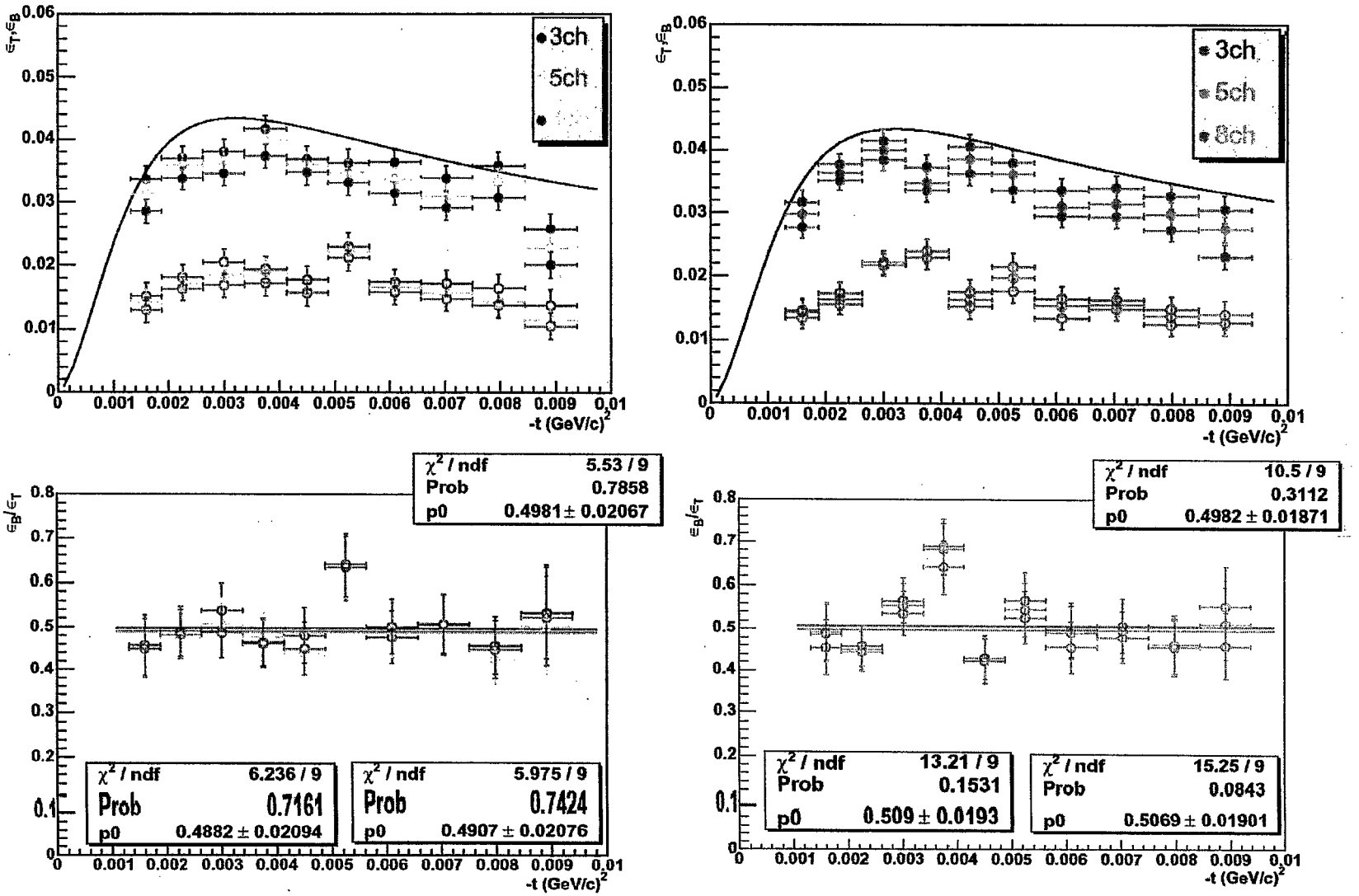
⊙ Statistical Advantage

✖RUN5 Backgound > 2×Run4 Background

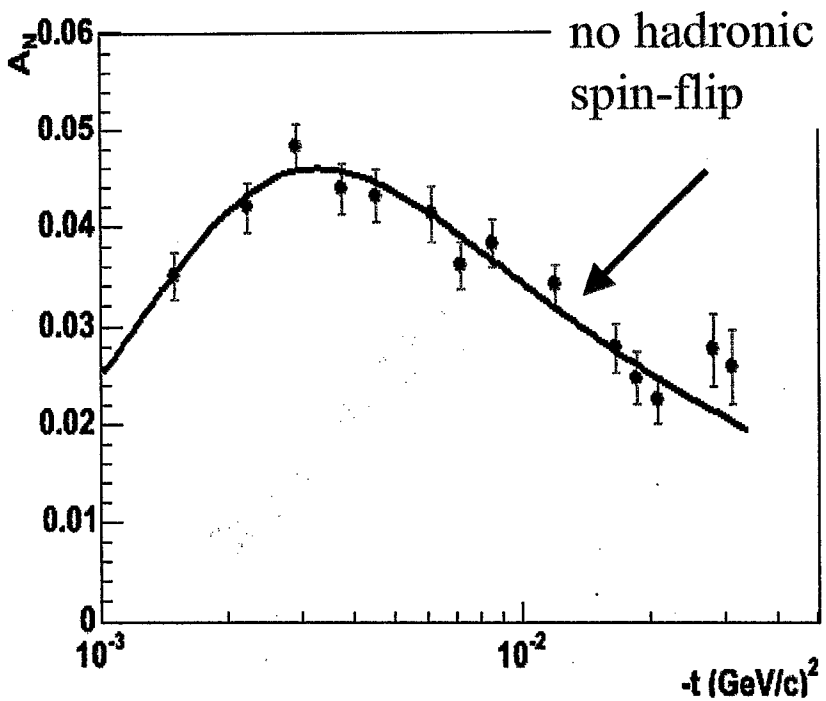


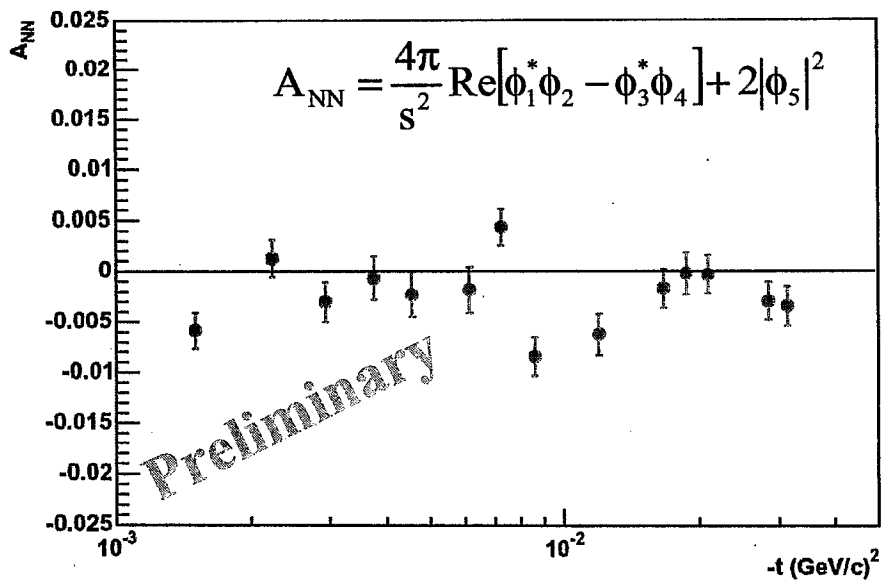


Online Asymmetry



Spin-Flip Amplitude in pp-A_N,A_{NN}

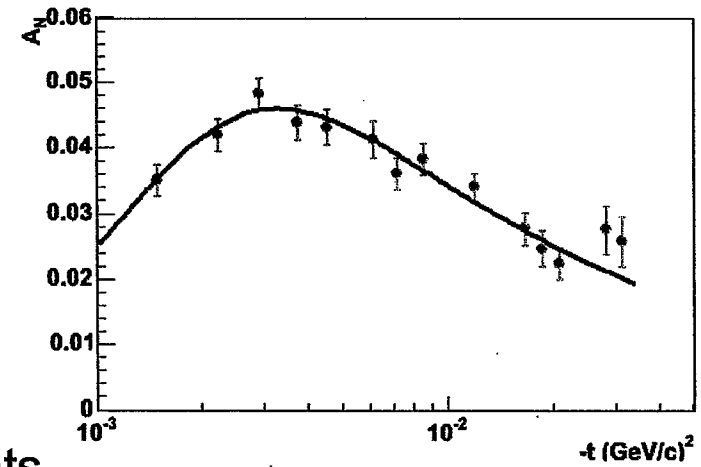


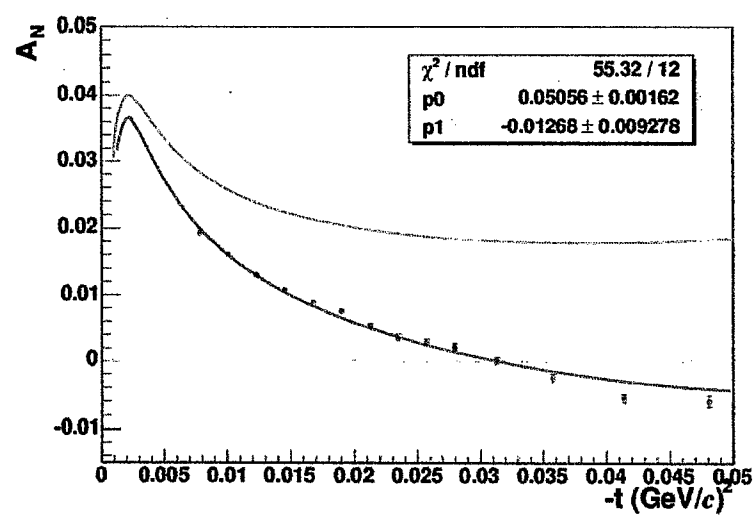


No need of Hadronic Spin-flip ➔ Contradictory to pC!

Summary

- pC
  - Improved ground
  - Explored -t>0.05GeV
  - Beam profile measurements
- pp
  - Sequential/Simultaneous measurments
  - Blue/yellow statistics × 2 Run4
- Hadronic Spin flip in A_N and A_{NN}
  - Crucial roll in pC
  - Very small in pp





The Pursuit of Polarized Gluon Distribution in the Nucleon with PHENIX

Abhay Deshpande

The pursuit of polarized gluon distribution in the nucleon with PHENIX

Abhay Deshpande
State University of New York at Stony Brook
Riken BNL Research Center

October 11, 2005

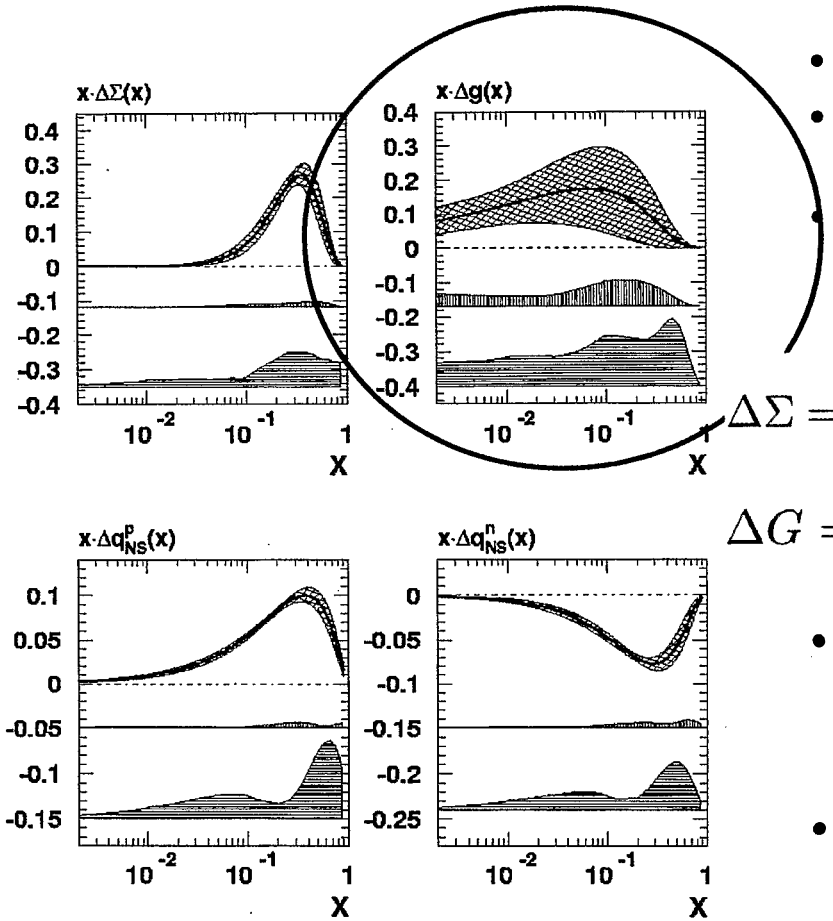
Overview

- Relevance of polarized gluon distribution in nucleon spin puzzle

- PHENIX Spin measurements towards understanding the spin puzzle
  - $A_{LL}(X^0)$ from Run-3 & Run-4 : a quick reminder
  - **RHIC Run-5 and expectation from PHENIX**
  - Run-6 and beyond

- Putting all data in perspective: a new initiative on combining world's spin data

Gluon Contribution to Nucleon Spin is Unknown



- SMC, PRD58, 112002 (1998)
- Analysis of world's all available data (SMC, SLAC, HERMES…)
- Quark contribution to nucleon spin well constrained but **gluon contribution has huge uncertainties**

$$\Delta\Sigma = \int_0^1 \Delta\Sigma(x, Q^2 = 1\mathrm{GeV}^2)dx = 0.23 \pm 0.05$$

$$\Delta G = \int_0^1 \Delta G(x, Q^2 = 1\mathrm{GeV}^2)dx = 1.0^{+1.4}_{-0.5}$$

- Since then many other analyses have been published with qualitatively identical results (E143 Collaboration, AAC Collaboration, E. Leader et al.)
- **New techniques to get to gluon spin necessary: RHIC Spin ideal**

Polarized Gluon Measurements with PHENIX

- Many channels involving polarized gluons in the initial state of scattering:
  - Allow independent constraints on the measurement
  - Have different experimental systematic uncertainties

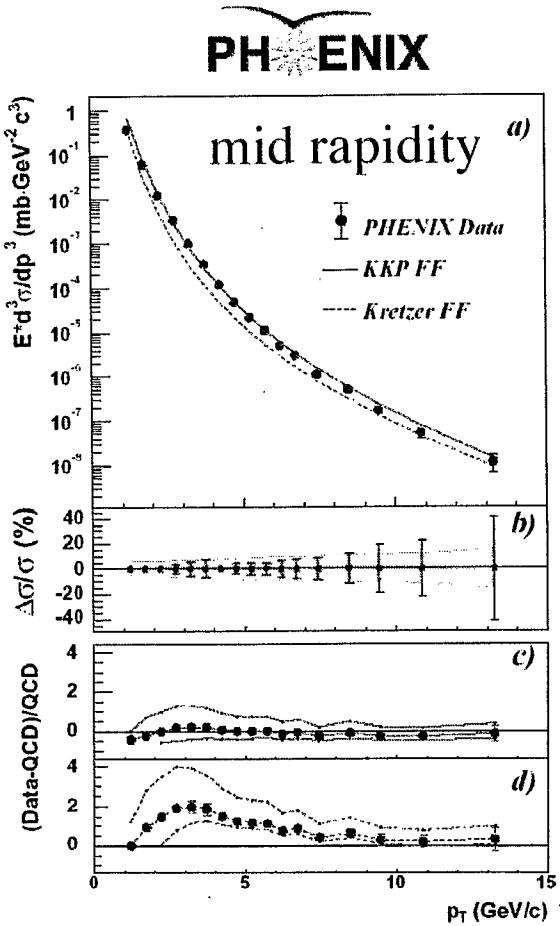
- Measurements with PHENIX detector
  - Inclusive neutral and charged pion production
    - 2003-2005/6

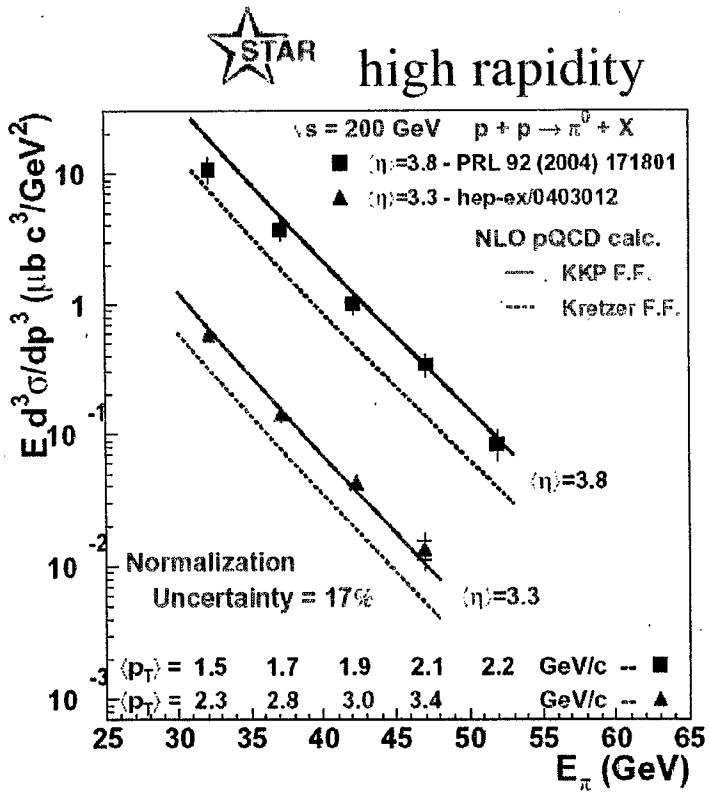
    ⇦ Large Cross Sections
  - Inclusive prompt photon production (details in K. Okada's talk)
    - 2005-2008/9

- Future upgrade (Si VTX TRK: A. Taketani) will allow additional measurements of gluon distribution using Xjet production, heavy quark production .... etc.
  - Beyond 2009 mostly in the 500 GeV CM program
  - Extend the kinematic range to lower x

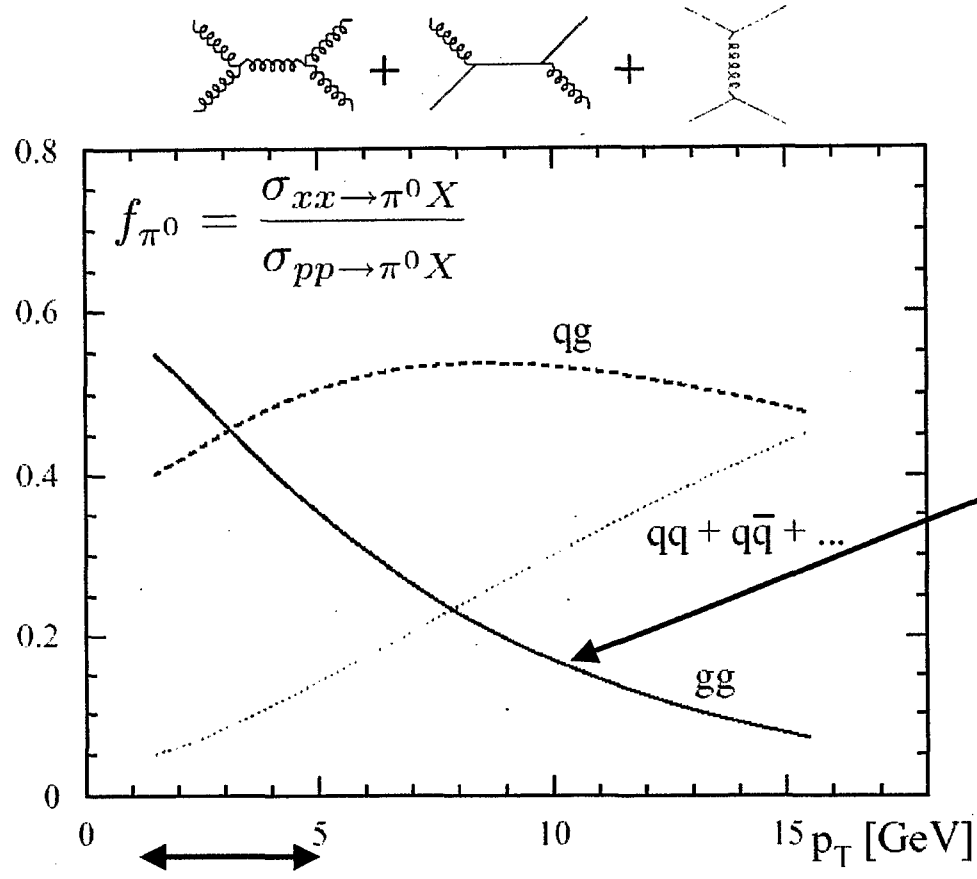
X(pp→X^0 X): Corner stone of RHIC measurements

- A well understood process: cross sections calculable in NLO pQCD in mid & high rapidy





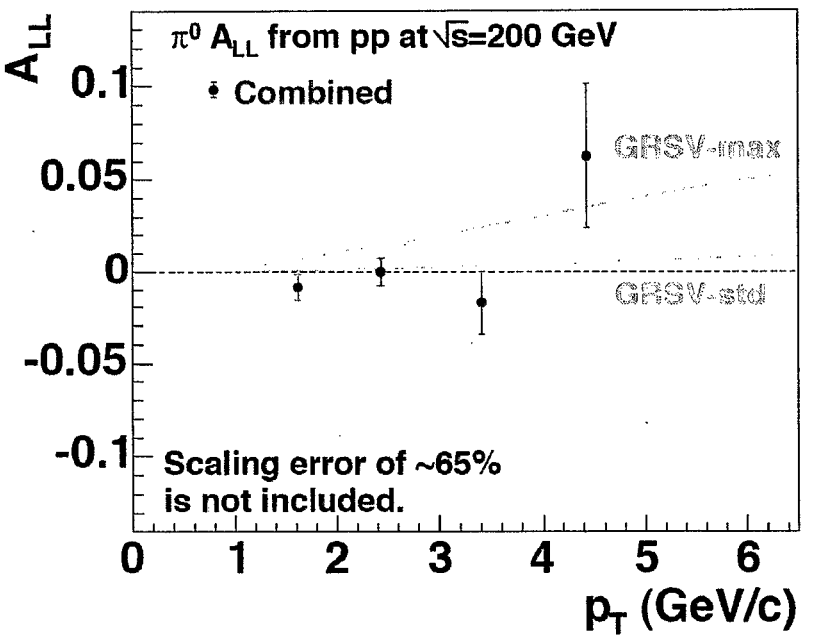
X^0 production and partonic contributions



gg + qg scattering dominant

- Fractional contribution of partonic scattering to total neutral pion production
- Gluon interactions dominate the low pT region
- In th every low pT (< 3 GeV) gg process dominates.
  - Asymmetry insensitive to the sign of gluon distribution
  - Needs measusurement at high pT (5-10 GeV) where qg process important &
  - Measurements of charged pions (see later)

PHENIX Run 3+4 vs. Gluon Parameterizations



Year	L pb^{-1}	P (%)	Fig. Of Merit: P^4L (nb^{-1})
2003	0.35	27	1.5
2004	0.12	38	3.3

Data seem to prefer low value of XG? X^2 probability 24% for GRSV-std and 3% for GRSV-max

GRSV-std corresponds to XG = 0.5 at $Q^2 = 1$ GeV^2 while GRSV-max corresponds to about 1.8 at the same scale.

Need to improve this measurement ASAP!

B. De Jaeger et al, Phys. Rev. D67, 0504005 (2003)

Run-5 pp: March 05 - May 05

- CAD hardware upgrades: Cold Siberian Snake in AGS commissioning, significantly increased NEG coated beam pipes….
- Highlights of RHIC accelerator performance:
  - Average ~47-50% beam polarization (routinely available)
  - Number of bunches in each ring 56 (beginning) --> 110 (towards the end)
  - **Delivered** luminosity 12.8 pb^{-1} in ~11 weeks of operation
  - Acceleration of polarized protons to 205 GeV/c, success demonstrated by (transverse orientation at experiments only)
    - Measured asymmetry by RHIC CNI polarimeters
    - PHENIX confirmed observation of forward neutron asymmetry
- PHENIX took its largest single sample of polarized pp data
  - 260 TB data, with various trigger setups
  - ~3.8 pb-1 of longitudinal double spin collisions, 0.16 pb-1 of transverse spin collisions,
  - All data transferred to CCJ almost in real time for preparing and starting the production quickly

3.8 pb-1 at 48% polarization corresponds to 205 nb^{-1} in Figure of Merit
~40 times better than 2003+2004!

Run-5 Neutral Pion Asymmetry Analysis status and prospects

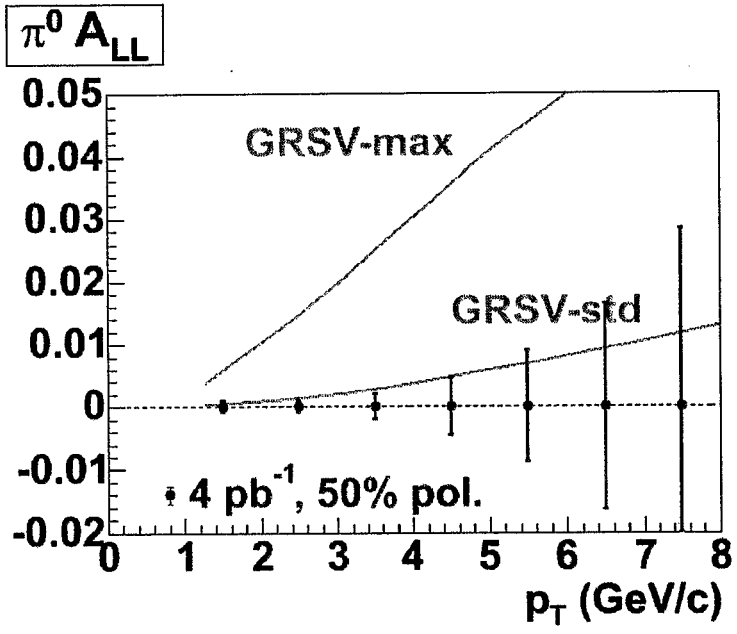
- Relative luminosity studies [K. Boyle(SBU)]: Interesting new effects observed:
  - First tests/trials with increased number of bunches in fills by CAD, studied and mostly understood
  - **Expect no major show stoppers, relative luminosity uncertainty presently estimated to be the same as in the previous years**

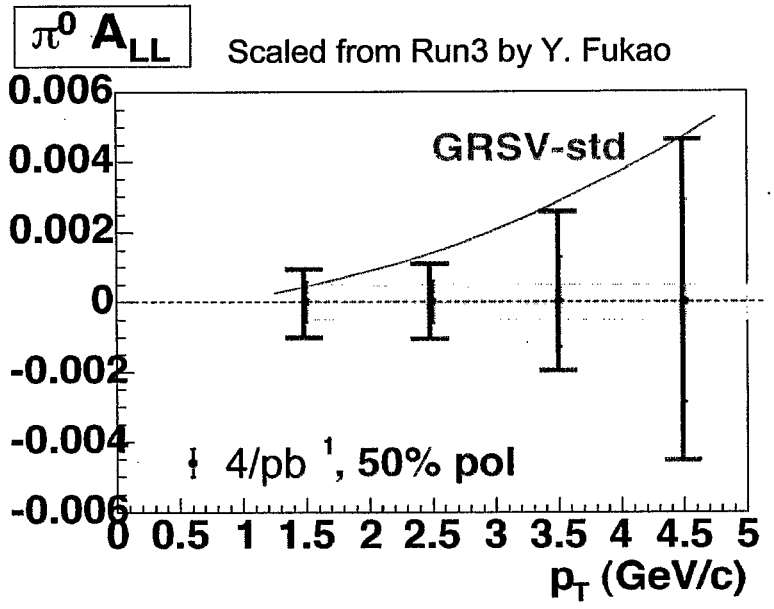
- Detector (EMCal, TOF) efficiency studies [Y. Fukao (Kyoto/RIKEN), K. Nakano (Tokyo/RIKNE)] -- **DONE**

- Beam polarization in Run-5 using online values
  - Preliminary values expected **(soon)**

- **$A_{LL}(X^0)$ Run-5 Result expected to be released at PANIC'05**
  - Kieran Boyle and Yoshi Fukao to present the results in a parallel session

Run-5 Neutral Pion Asymmetry



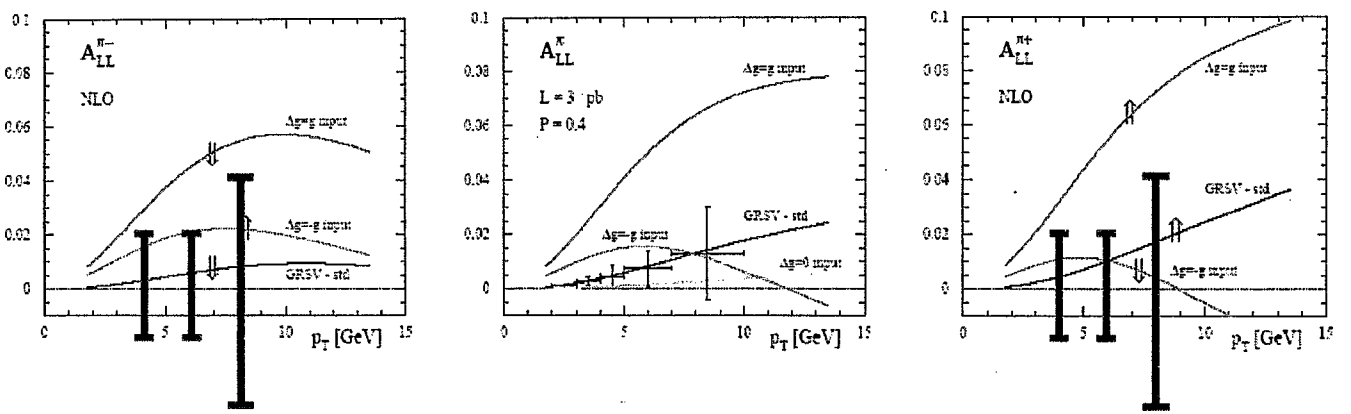


- GRSV std corresponds to a very small polarized gluon integral
  - XG ~ 0.5 at Q^2=1 GeV^2
- While Run 3+4 seem only to rule out GRSV-max parameterization, **Run 5 data will allow us to get the first definitive estimate for the magnitude of the polarized gluon distribution's first moment**

Charged pion asymmetries: Sign of XG?

- Run-5 neutral pion asymmetry estimates & charged pion asymmetries will resolve the sign of the XG as well!

π^- π^0 π^+



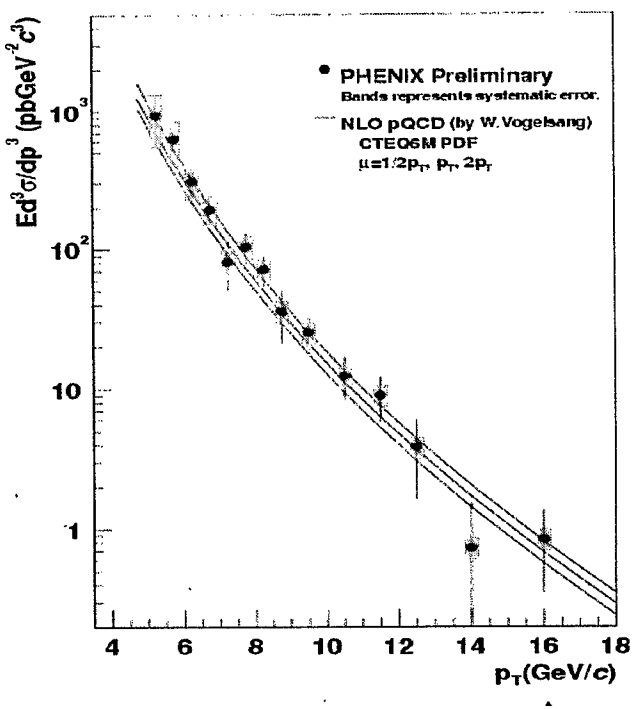
idea: qg starts to dominate for $p_T \gtrsim 5\,\mathrm{GeV}$ and $D_u^{\pi^+} > D_u^{\pi^0} > D_u^{\pi^-}$, $D_g^{\pi^+} = D_g^{\pi^-}$

expect: sensitivity to sign of Δg, e.g., positive Δg: $A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$

M. Stratmann et al.

Plans for Run-6 & Beyond

- Many other efforts underway for XG measurements in the near future:
  - Neutral pions result consolidation + charged pion asymmetries
  - Direct photon (see K. Okada's talk)
  - A_{LL} of Jet-like cluster: Jet surrogates in PHENIX! (K. Nakano, APS/DNP)



- By 2009 we expect ~90 pb^{-1} luminosity in PHENIX at 200 GeV CM accumulated in 35 weeks of pp running
  - Completion of 200 GeV CM program

- Si VTX TRK will be available at this time and **500 GeV** program begins
  - XG with g-jet co-incidence
  - XG with heavy quark production

Global Analysis of Polarized Scattering Data : A new initiative

- We must extract maximum information out of the existing and anticipated data (including the polarized DIS and RHIC pp)
  - **Require:** "A Global Analysis" of all available data using the state-of-the-art theoretical formulism and tools
  - **Emphasis**: Careful evaluation of experimental and theoretical uncertainties
  - General method clear & obvious, details of including pp at NLO complicated, but W. Vogelsang et al have developed early ideas

- **A new initiative is being considered with RHIC experimentalists, theorists & members of CTEQ collaboration:**
  - **CTEQ willing to provide the tools for such an analysis**
  - **BNL/Stony Brook theory & other CTEQ colleagues are willing to help!**

- A group of us will start this shortly across collaborations with an aim to develop this as the 200 GeV RHIC Spin program ramps up

Concluding Thoughts

- These are exciting times for RHIC Spin!

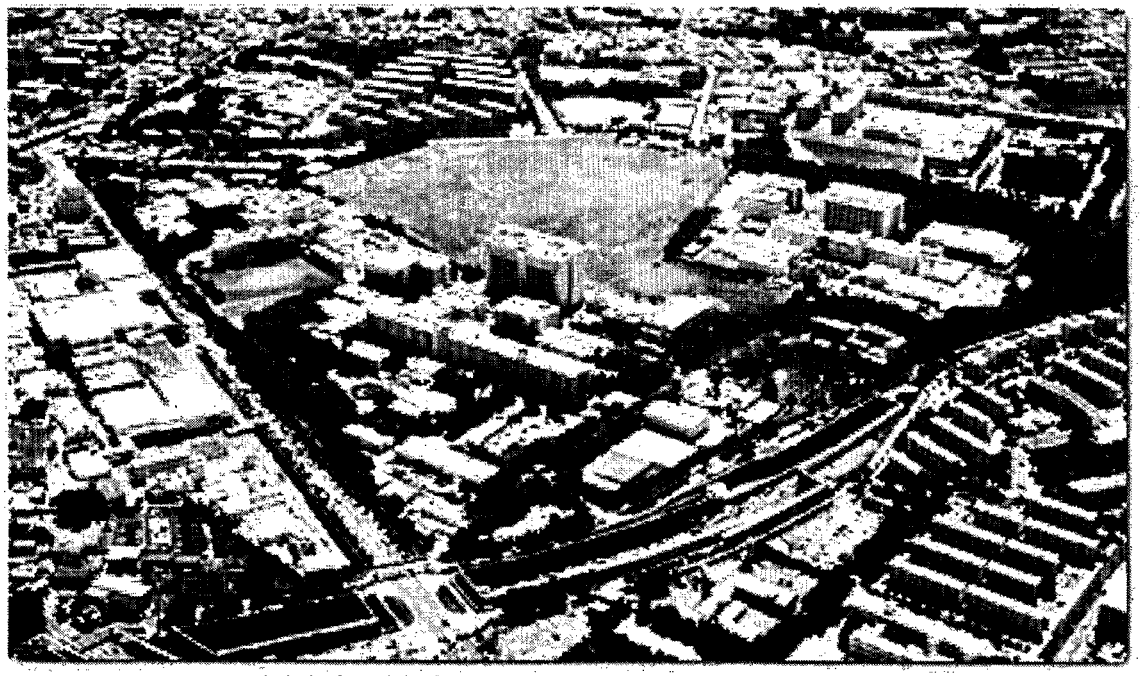
- First conclusive results on XG from RHIC may be just around the corner
  - Neutral pion production has paved the way and charged pion & direct photon analyses will follow
  - Intermediate term outlook is exciting due to the anticipation of a huge amount of RHIC polarized pp data

- Utilizing these data in the most comprehensive way to extract maximum knowledge is essential & will require the a CTEQ/MRST like effort. This needs to start now.

Spin Fest - 2005 Data Analysis

Yuji Goto

Spin Fest – 2005 Data Analysis



▲Wako Main Campus・Wako Institute

RBRC Review

October 10, 2005

Yuji Goto

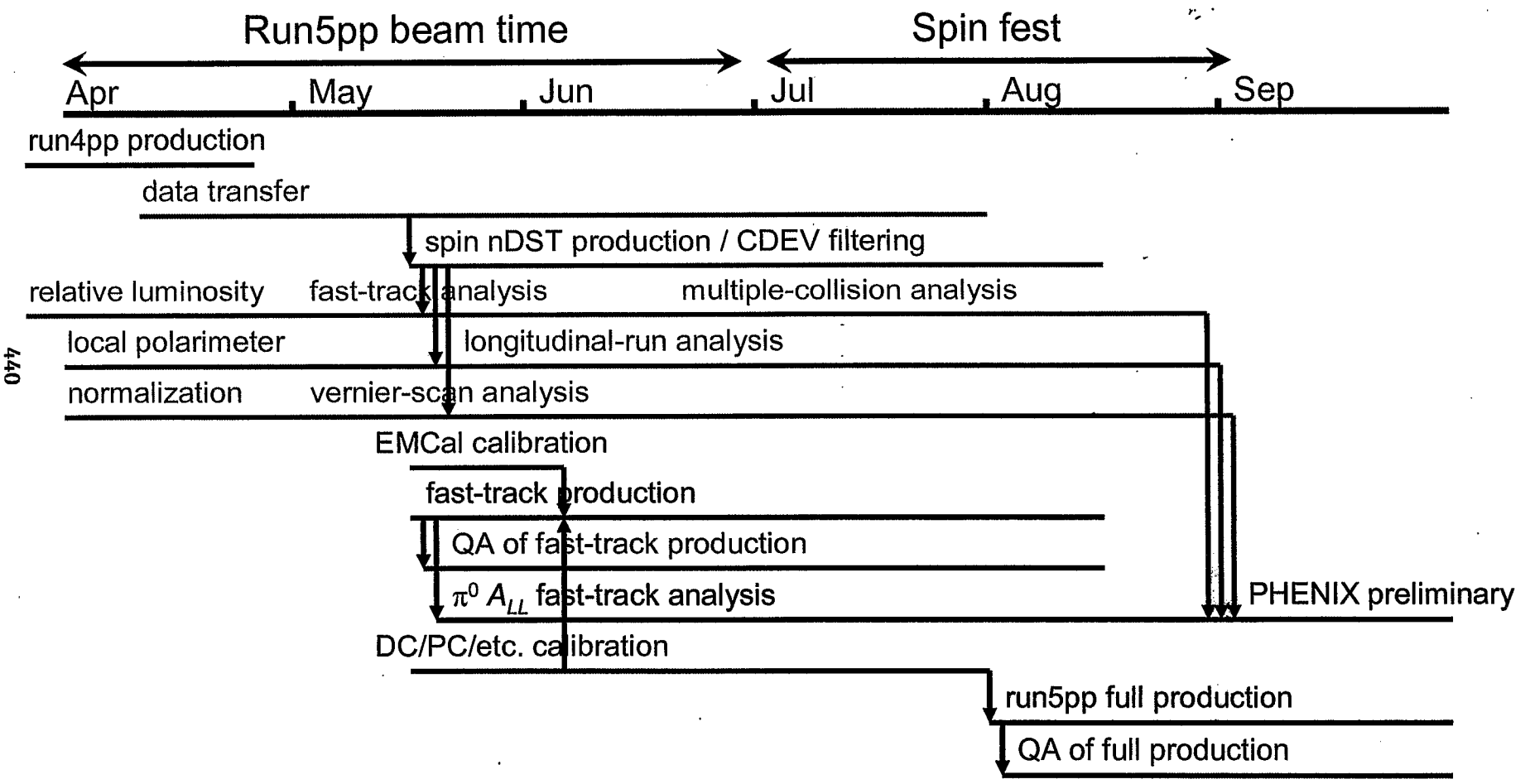
PHENIX Spin Fest

- July 11th – September 2nd
  - just after 2005 polarized-proton run ended on June 25th …
  - Pacific-spin 05 symposium in Tokyo: July 5-8
- at radiation laboratory, RIKEN Wako institute
  - two meetings every week connecting to BNL etc. by telephone
    - regular Spin PWG meeting (every Thursday morning: 9am-11am)
    - extra Spin Fest meeting (every Tuesday morning: 9am-11am)
  - theory lecture course: July 25-29
  - seminars by participants and guests every week
    - every Monday afternoon: 2pm-
    - coordinator: Kiyoshi Tanida
  - workshop at Nikko: August 17-19

Goals

- Fast-track analysis of central-arm data in 2005 polarized-proton run
  - physics goals: π^0 A_{LL}, direct-photon cross section, …
  - monitoring of quality of data as it is being produced, alerting the group to possible hardware software problems and if there are any serious real physics problems …
  - on BNL side, supporting this effort from a distance when needed: input from detector groups and specialists, …
  - physics analysis of transverse physics data will start immediately …
- Preparation of full production of central-arm & muon-arm data
  - to start in or after the spin fest …
- Formation of a strong spin analysis group
  - develop specializations, know each other's qualities, and learn to work as a cohesive group, …

Analysis plans



as of May 18 …

Participants

		arrival	departure	6/27	7/4	7/11	7/18	7/25	8/1	8/8	8/15	8/22	8/29
Kenichi Nakano	TITech	6/28	8/24										
Ming Liu	LANL	6/29	7/14										
Hiro Hieijima	UIUC	7/4											
Ralf Seidl	UIUC	7/5	7/20										
Oleg Eyser	UCR	7/5	9/2										
Mickey Chiu	UIUC	7/6	7/25										
Manabu Togawa	Kyoto	7/7	9/2										
Matthias Perdekamp	UIUC/RBRC	7/8	7/14										
Doug Fields	UNM/RBRC	7/8	7/15										
Edward R. Kinney	Colorado	7/8	7/16										
Frank Ellinghaus	Colorado	7/8	8/3										
Kenneth N. Barish	UCR	7/10	7/25										
Ran Han	Peking	7/10											
Joseph Seele	Colorado	7/11	8/1										
Petr Mikes	Prague	7/11	8/10										
Robert Bennett	SBU	7/11	9/2										
Kieran Boyle	SBU	7/11	9/2										
Waled Emam	UCR	7/11	9/3										
Jan Rak	UNM	7/12	7/20										
Antonin Kral	Prague	7/13	8/10										
Kensuke Okada	RBRC	7/16	8/8										
Dave Kawall	UMass/RBRC	7/17	7/31										
Gerry Bunce	BNL/RBRC	7/25	7/30										
Abhay Deshpande	SBU/RBRC	7/25	8/8										
Kazuya Aoki	Kyoto	7/25	8/8										
Yoshi Fukao	Kyoto	7/25	9/2										
Sasha Bazilvsky	BNL	8/2	8/20										
Astrid Morreale	UCR	8/4	8/26										
Tomas Liska	Prague	8/7	8/29										
Naohito Saito	Kyoto/RBRC	8/22	9/2										

- from US, Czech, China, and Japan
  - 11 staff members
  - 7 postdocs
  - 12 students
- and many people who stay at BNL, RIKEN Wako, etc.

Coordinators and supporting staffs

- Overall coordinators of the analysis
  - Yuji Goto, Kiyoshi Tanida (at RIKEN), and Abhay Deshpande (at BNL)
- Period coordinators

	at RIKEN	at BNL
– June 28 –	Ming Liu (LANL)	
– July 11 –	Ken Barish (UCR)	Wei Xie (RBRC)
– July 25 –	Abhay Deshpande (SBU/RBRC)	Imran Younus (UNM)
– August 8 –	Yuji Goto (RIKEN)	Dave Kawall (UMass/RBRC)
– August 22 –	Naohito Saito (Kyoto)	Mickey Chiu (UIUC)

- Supporting staffs
  - Yasushi Watanabe (computer and network in general)
  - Takashi Ichihara, Satoshi Yokkaichi and Souichiro Kametani (CCJ)
  - Hisa Torii (CCJ production)
  - Ms. Kiyama (many many supports in general) !!!

Technical tasks

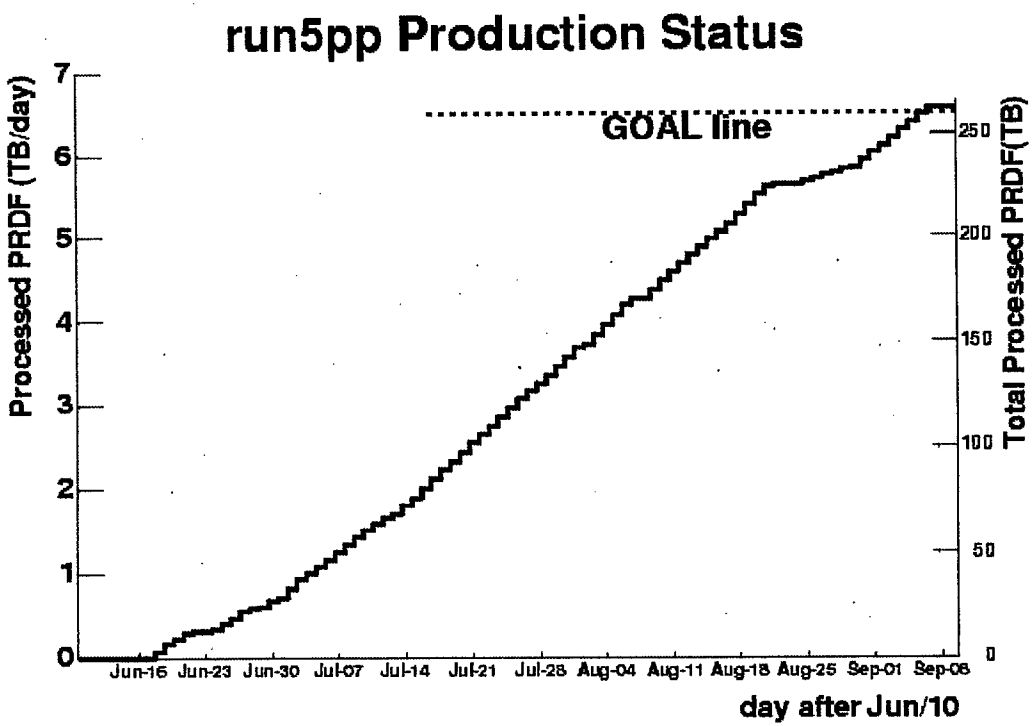
• data transfer	Mickey, Satoshi, Yasushi, …
• relative luminosity	Dave, Yoshi, Kieran, Robert, Imran, Sasha, Oleg, …
– fast track analysis	
– multiple-collision analysis	
• local polarimeter	Manabu, Kieran, Joe, …
– rotator commissioning done !	
– longitudinal-run analysis	
• normalization	Dave, Robert, Sasha, Oleg, Joe, …
– vernier-scan analysis	
• fast-track production	Hisa and production team …
– EMCal calibration/QA	Kenichi, Yoshi, Takuma, …
– PC/DC calibration/QA	Kazuya, Manabu, …
– ERT analysis	Kensuke, …
– π^0 A_{LL} analysis	Sasha, Kieran, Yoshi, …
• full production	Hisa and production team …
– calibration/QA	Imran, …
• simulation (if necessary …)	
– Fast MC	
– full PISA production	

Physics analysis

- π^0
  - Sasha, Kieran, Yoshi, Dave, Imran, …
- direct photon
  - Kensuke, Robert, Kenichi, Sasha, Takuma, Dave, …
- η
  - Frank, Joe, Hiro, …
- $h^{\pm}/\pi^{\pm}$
  - Kieran, Waled, …
- jet
  - Kenichi, …
- $e^{\pm}$
  - Manabu, …
- Λ
  - Ran, Kazuya, …
- 200 GeV transverse-polarization data
  - Mickey, Oleg, Christine, Hiro, …
- 410 GeV transverse-polarization data
  - Manabu, …

CCJ production

- Production team
  - Hisa Torii (RIKEN), Oleg Eyser (UCR), Joe Seele (Colorado), Ran Han (Peking), Antonin Kral, Petr Mikes and Tomas Liska (Prague)
- Production contributers and monitoring shifters
  - Mickey Chiu (UIUC, analysis coordinator), Frank Ellinghaus (Colorado, data transfer), Imran Younus (UNM, shift in US), Mikhail Stepanov (NMSU, shift in US), Astrid Morreale (UCR, shift in Japan), Christina Hagemann (UNM, shift in US) and Kazuya Aoki (Kyoto, shift in Japan)



Fast-track production of 260 TB data (!) finished on September 6 !!

Weekly seminars

- July 11:
  - 14:00 Sivers measurement using back to back di-hadrons by Mickey Chiu (UIUC)
- July 20: (Wednesday)
  - 14:00 Testing fundamental symmetries with molecules by Dave Kawall (UMass/RBRC)
  - 15:30 High pT measurements in PHENIX by Ken Barish (UCR)
- July 25:
  - 14:00 Silicon detector development and radiation hardness for nuclear and high energy physics experiments at BNL and around the world by Zheng Li (BNL Instrumentation)
  - 15:30 High statistics search for Theta(+) in gamma+d -> K(+) K(-) p (n) reation by Tsutomu Mibe (Ohio)
- August 1:
  - 14:00 Absolute polarimetry in RHIC -- How to measure the beam polarization? What is the principle? by Hiromi Okada (Kyoto)
  - 15:30 Silicon-Tungsten Calorimeter for the Forward Direction in the PHENIX Experiment at RHIC by Itaru Nakagawa (RIKEN)

Theory lectures

- July 25th (Mon) – 29th (Fri)

Outline of the lectures

Lecture 1: basic ideas; exploring the QCD final state

Lecture 2: origin of singularities; infrared safety

Lecture 3: QCD initial-state; factorization; renormalization

Lecture 4: more on factorization & renormalization; pdfs

Lecture 5: applications in hadron-hadron collisions; pdfs

Lectures on Perturbative QCD
or from basic principles to current
applications by Marco Stratmann
(Regensburg Univ.)

Contents

Parton Distribution Functions (PDFs)

1. **Unpolarized PDFs**
2. **Polarized PDFs: General Analysis Method**
3. **Polarized PDFs: Recent Progress**
4. **RHIC-Spin and Other Topics**

---

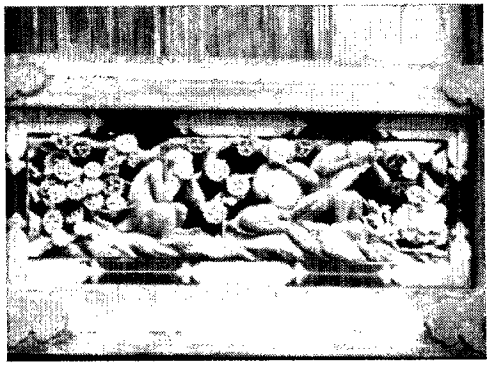
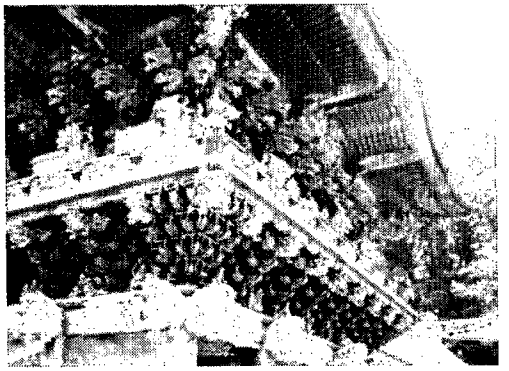
5. **K. Sudoh, Hadron Productions and Polarized PDFs**

July, 25-28 2005 PHENIX Spin Fest @ RIKEN Wako 6

Determination of Polarized
Parton Distribution Functions
by Shunzo Kumano (KEK)
and Kazutaka Sudoh (KEK)

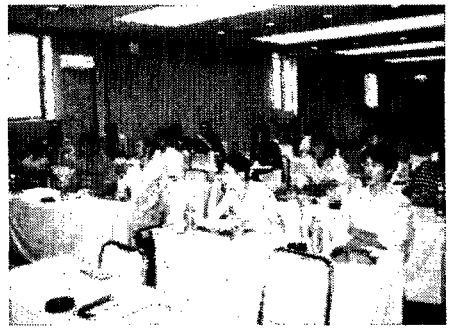
and after-lecture discussions …

Workshop at Nikko

- Joint workshop of PHENIX spin fest and RIKEN radiation laboratory
  - more than 20 participants
  - at Kinugawa Onsen Hotel
- August 17 (Wed):
  - 9:00 RIKEN Wako → bus→ 12:00 Nikko
  - 12:00-17:00 lunch and excursion around Nikko Toshogu shrine
  - 17:00 to Kinugawa Onsen Hotel and dinner
  - 19:00-21:00 *** session 1 ***
- August 18 (Thu)
  - 9:00-12:00 *** session 2 ***
  - 12:00-15:00 lunch and official excursion to Ryuoh-Kyo
  - 15:00-18:00 *** session 3 ***
  - 18:00 banquet
- August 19 (Fri)
  - 10:00 hotel →bus→ deep Nikko: excursion at Kegon fall, Chuzenji lake, etc.
  - 16:00 Nikko →bus→ 19:00 RIKEN Wako

Workshop at Nikko



- Session 1 – chair: Yasushi Watanabe (RIKEN)
  - Kazutaka Sudoh (KEK)
  - Sergei Kondrashev (ITEP) Laser Ion Source of Highly Charged Ions for Synchrotrons
  - Takeshi Kanesue (Kyushu U.) ion production with laser
  - Megumi Naruki (RIKEN) In-medium modification of rho/omega mesons
  - Ryotaro Muto (RIKEN) In-medium modification of phi meson
  - Maki Kurosawa (SUT)
- Session 2 – chair: Hideto Enyo (RIKEN)
  - Sasha Bazilevsky (BNL) Pi0 cross section and A_LL in pp Run5: status and expected sensitivities
  - Kieran Boyle (SBU) Relative Luminosity un Run5
  - Robert Bennett (SBU) Vernier Scans in Run5
  - Vladimir Rykov (RIKEN) Status report on the analysis of spin transfer to anti-Lambda-hyperon from longitudinally polarized protons
  - Ran Han (Peking) Spin flavor structure of Nucleon via W Production
  - Yuji Goto (RIKEN) Transverse back to back Di-Hadron Jets
  - Yasushi Watanabe (RIKEN) CCJ - past, present, and future
  - Tomas Liska (Prague) Massive Data Production on Distributed Computational Environment
- Session 3 – chair: Koji Nakai (SUT)
  - Oleg Eyser (UCR) Transverse single spin asymetries in charged hadrons
  - Waled Emam (UCR) A First Look at the Charged Pion
  - Kiyoshi Tanida (RIKEN) Single spin asymmetry in very forward particles in polarized p-p collison
  - Atsushi Taketani (RIKEN) PHENIX VTX Upgrade
  - Junkichi Asai (RIKEN)
  - Yoshiyuki Onuki (RIKEN) PHENIX/Pixel detector assembly

Achievements and future outlook

- Fast-track production of central-arm data in 2005 polarized-proton run DONE
- Detector calibration, QA, analysis of the relative luminosity, local polarimeter, normalization, etc. ONGOING
- Preliminary π^0 A_{LL} data of 2005 polarized-proton run will be shown at PANIC05 conference (Santa Fe, October 24-)
- Full production of central-arm & muon-arm data will start SOON
- Many new longitudinal & transverse spin results of variety of physics channels will be obtained:
  - direct photon, η, $\pi^{\pm}$, jet, $e^{\pm}$, $\mu^{\pm}$, J/ψ, Λ, 200 GeV & 410 GeV transverse-polarization data, …
- Spin analysis group is formed stronger involving many US/Europian/Asian institutions
- It is worthwhile to plan the similar activity for future runs !!!

Relative Luminosity Measurement at PHENIX

David Kawall

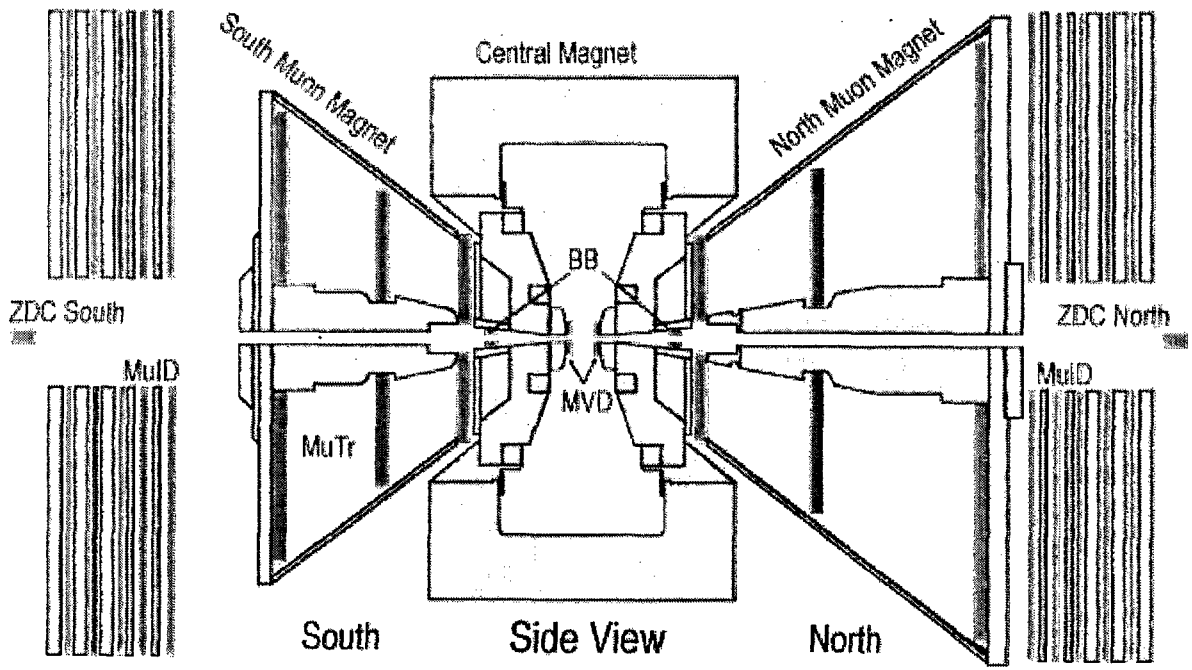
$$
\begin{aligned}
A_{LL} &= \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \\
&= \frac{1}{|\langle P_b P_y \rangle|} \cdot \frac{N_{++} - R \cdot N_{+-}}{N_{++} + R \cdot N_{+-}}; \quad R = \frac{L_{++}}{L_{+-}} \\
\frac{\partial A_{LL}}{\partial R} \delta R &\approx \frac{1}{2|\langle P_b P_y \rangle|} \delta R
\end{aligned}
$$

- To measure 1% asymmetry with $P_{beam} \approx 50\%$, need $\delta R < 10^{-3}$
- Higher polarization reduces sensitivity to uncertainty in R
- Order of magnitude requirement : $\delta R \leq \text{few} \times 10^{-4}$

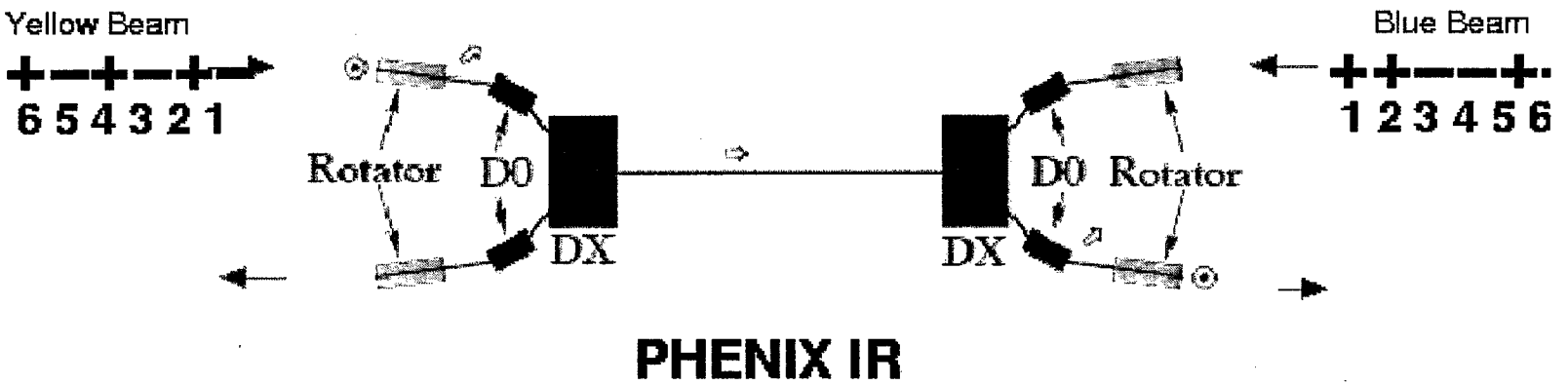
- How do measure relative luminosity?
- What difficulties do we expect?
- What should we do? (Work in progress)

Relative Luminosity Measurement at PHENIX

- Collisions defined by coincidence of signals in Beam-Beam Counters (BBCs)
- Located at ± 1.44 m from interaction point, cover $\Delta\phi = 2\pi,\ 3.0 \leq |\eta| \leq 3.9$
- Average hit time is formed from PMTs in north and south BBC arms separately
- From difference of north and south BBC hit times can reconstruct z of vertex
- Central arm acceptance requires event vertex $|z| < 30$ cm, muon arms less restrictive
- Have separate scalers for each bunch pair to measure collison rate for different helicity combinations
- Measure R with scalers attached to this minimum-bias trigger, $R = \frac{BBC_{++} + BBC_{--}}{BBC_{+-} + BBC_{-+}}$



PHENIX Interaction Region



- Same pairs of bunches always collide
- Since bunches are accelerated individually, luminosity of each bunch pair is different

Complications in Extracting R as Luminosity Increases

- At design luminosity, we expect ≈ 1 pp collision/crossing
- 70 percent of all crossings may contain 2 or more pp collisions
- At least two complications will result :

(1) BBC scaler counting minimum-bias triggers only counts 0 or 1 pp interactions/crossing

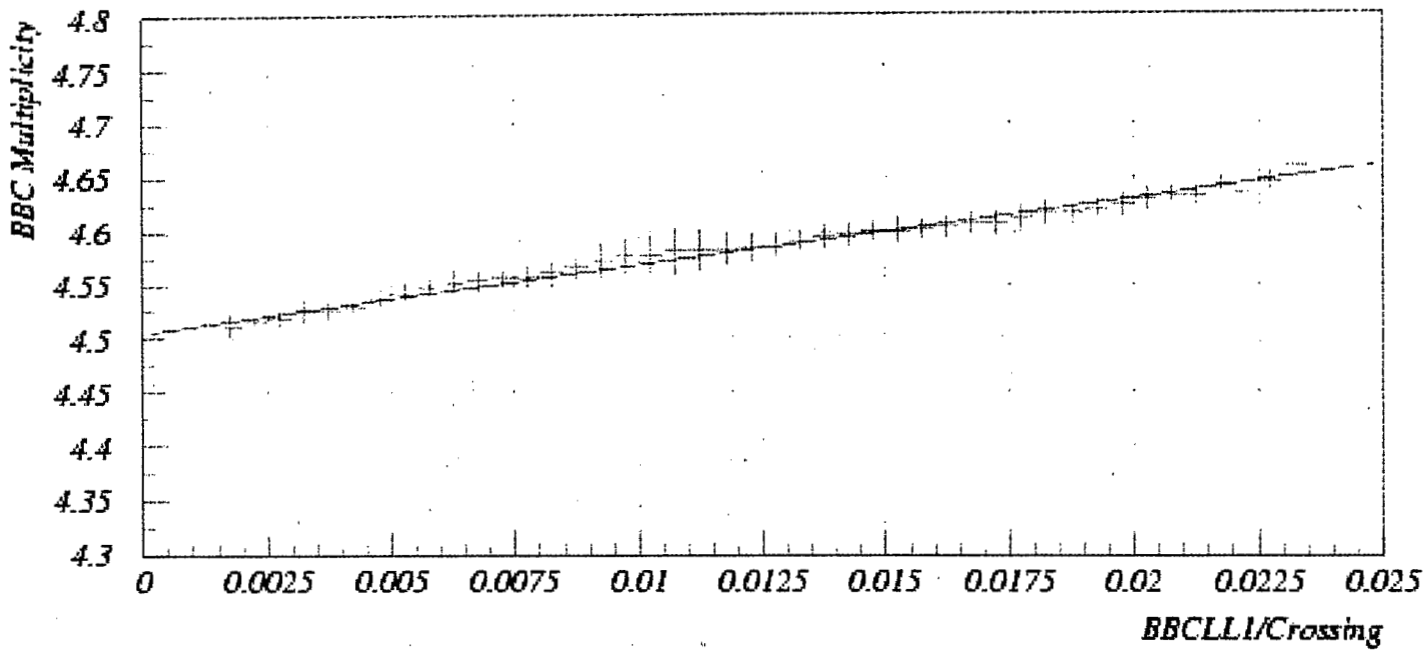
- μ=average number of pp interactions/crossing passing vertex cut,
  ϵ=probability that one arm of BBC detects the collision,

$$\frac{\text{Number of BBC Triggers}}{\text{Number of Crossings}} = 1 - e^{-\mu\epsilon}\left[2 - e^{-\mu\epsilon(1-\epsilon)}\right]$$

- Minimum-bias trigger rate not simple function of luminosity
- Would do better by measuring something *linear* in pp interactions/crossing
- Accuracy in extracting $R = \mu_{++}/\mu_{+-}$ depends on knowledge of $\epsilon = \epsilon(z)$
- Even if we know $\epsilon(z) \Rightarrow$ still need to know true vertex distribution

Partial Solution to Determining Relative Luminosity

- In Run 5 we recorded BBC phototube multiplicity/crossing in PHENIX scalers
  - Linear in luminosity to much higher pp rates than BBC trigger rate

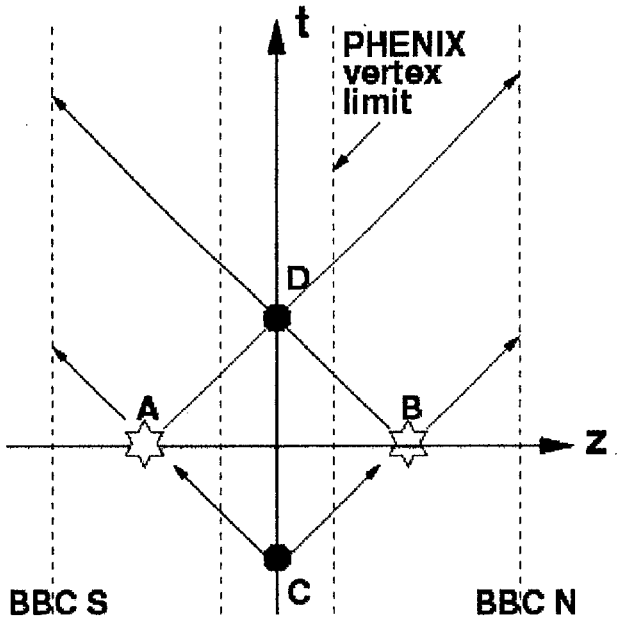


- Clear evidence in Run 5 of multiple collisions/crossing
- Multiplicity determined with high precision for each crossing in each run
- But - collisions outside of PHENIX vertex acceptance also contribute to multiplicity
- To extract luminosity requires knowledge of the vertex distribution and $\epsilon(z)$

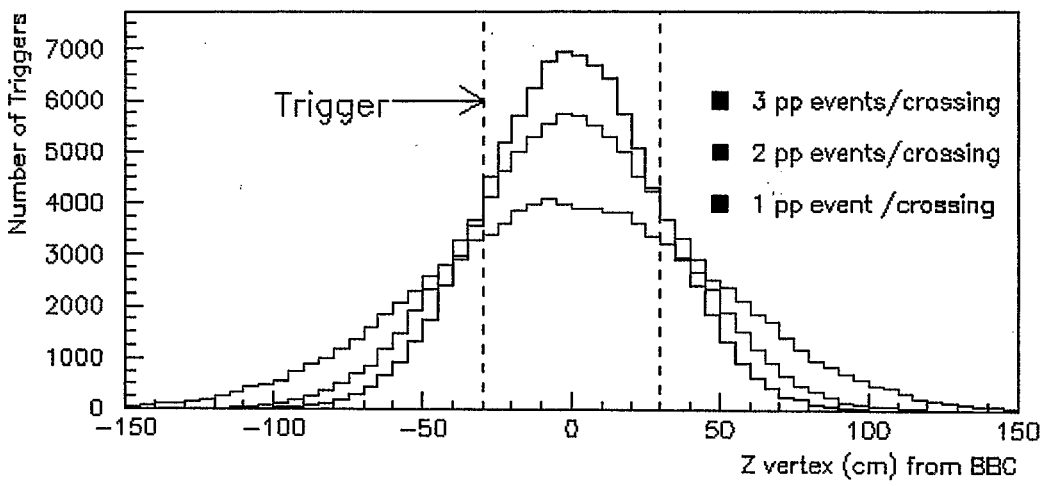
Second Complication : Determining the Z Vertex with the BBC

(2) We need to measure luminosity delivered inside PHENIX vertex cuts ($\pm$ 30 cm)

- With multiple pp interactions/crossing, will count events outside of PHENIX acceptance

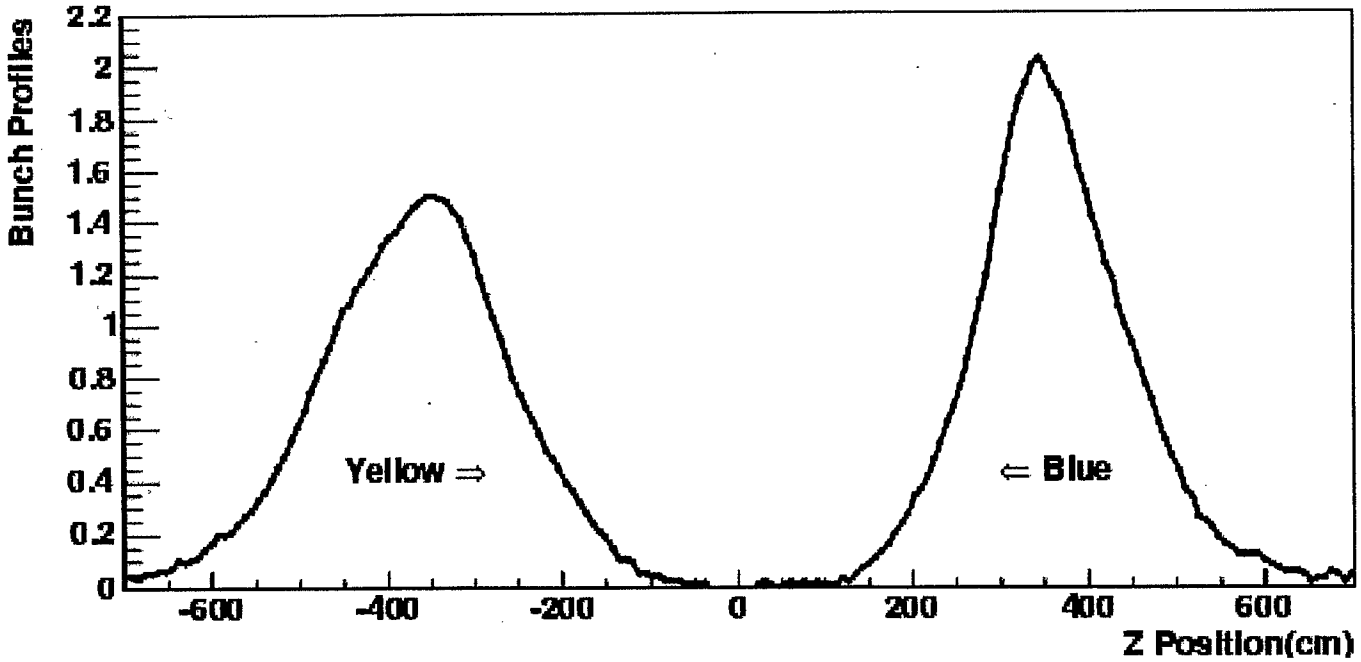


- Collisions at A & B outside PHENIX vertex
- Can be interpreted as collisions at C and D
- Vertex reconstructed by BBC is distorted
- Measurement of luminosity inside vertex limits distorted

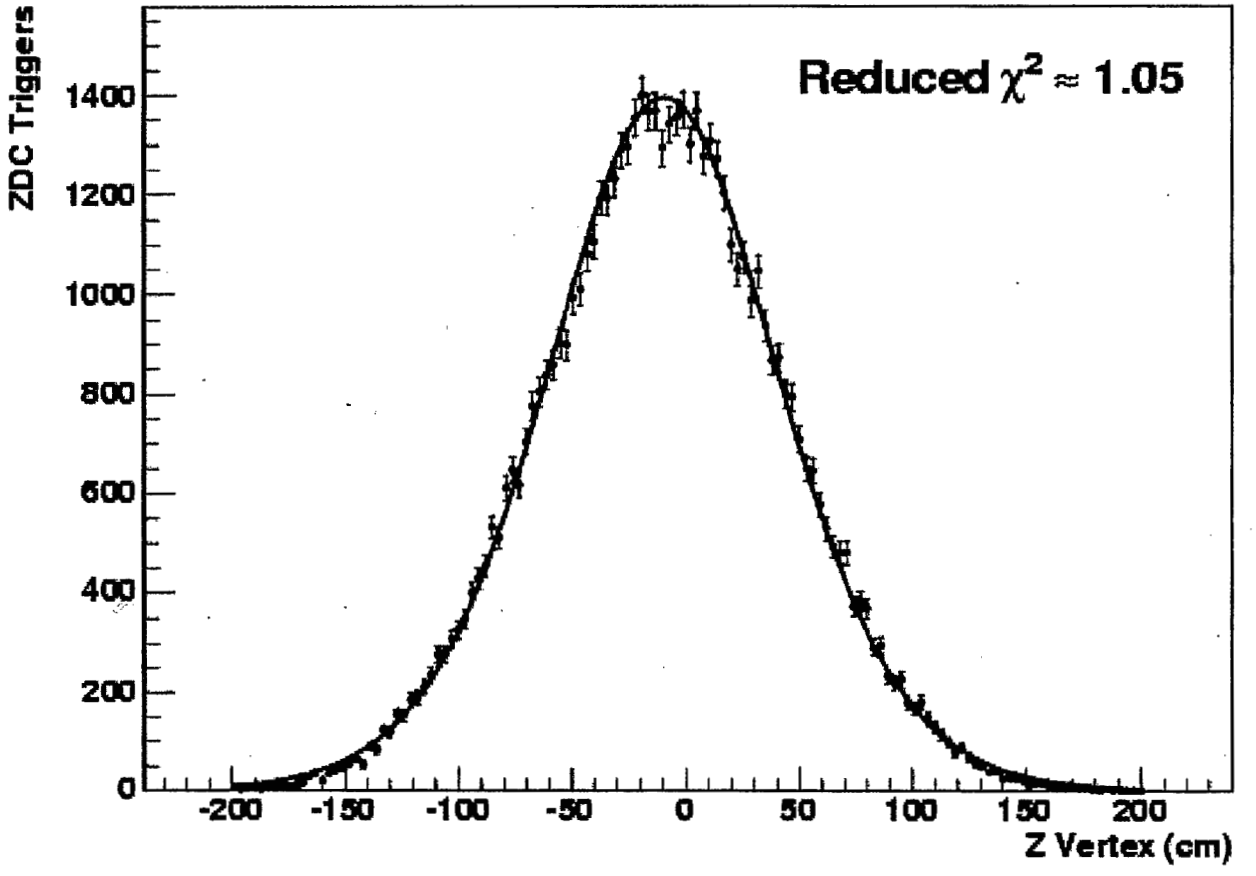


Possible Solution : Determine Vertex Distribution with Wall Current Monitor

- Image charges induced in beam pipe by bunched protons are shunted through resistors and resulting voltage sampled at 4 GHz
- Provides longitudinal profile of each blue and yellow bunch
- Can attempt to predict vertex distribution



Predicted Vertex Distribution using Wall Current Monitor



- Construct vertex from WCM data, account for $\beta^* = 1$ m, smear with ZDC resolution
- Fit 50 crossings, $\chi^2/N \approx 1.13$ for $N \approx 250$, vertex RMS predicted to 2 mm
- Predicts "true" vertex in absence of effects of multiple collisions/crossing
- (ZDCLL1 trigger selects $|z|$ <150 cm)

Possible Approach to Determining Relative Luminosity

- ZDC vertex predicted from wall current monitor is reasonable
- Comparing vertex predicted with WCM to observed BBC vertex yields $\epsilon(z)/\epsilon(0)$
- For each crossing, knowledge of WCM profiles, $\epsilon(z)$, and BBC multiplicity may allow us to extract relative luminosity in high rate environment
- All assumptions can be cross-checked with observed vertex distribution and trigger rate
- Cross-talk in WCM needs to be reduced
- Should get spin flipper commissioned :
  - Allows us to flip polarization of all bunches in a beam
  - Then individual bunch pairs can have $\int \mathcal{L}_{++}dt \approx \int \mathcal{L}_{+-}dt \approx \int \mathcal{L}_{--}dt \approx \int \mathcal{L}_{-+}dt$
  - Dramatically reduced uncertainties in R from vertex shape and multiple collisions/crossing
  - Relative luminosity $R \approx 1$ by construction
- Other approaches still being considered

Measurement of Direct Photons in $\sqrt{s}$ = 200 GeV p+p Collisions

Kensuke Okada

Measurement of Direct Photons in $\sqrt{s}$=200GeV p+p collisions

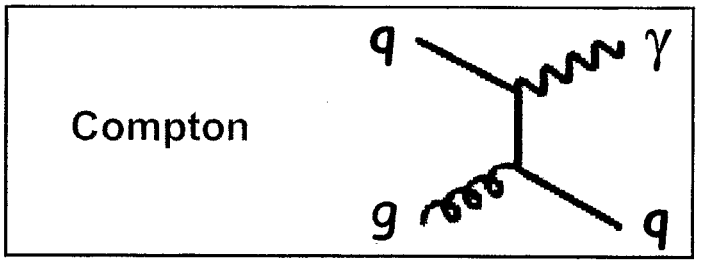
K.Okada

RBRC review

October, 2005

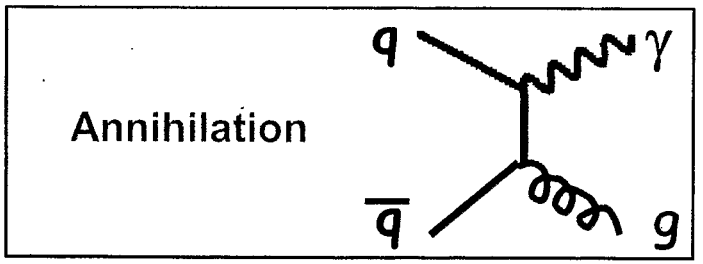
Motivations

—Test of our theoretical understanding based on QCD
—Direct information on gluon distribution in the proton
With polarized beam at RHIC, it is a probe for gluon polarization
—Reference for A+A collisions



80~90%

Dominant



20~10%

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Data

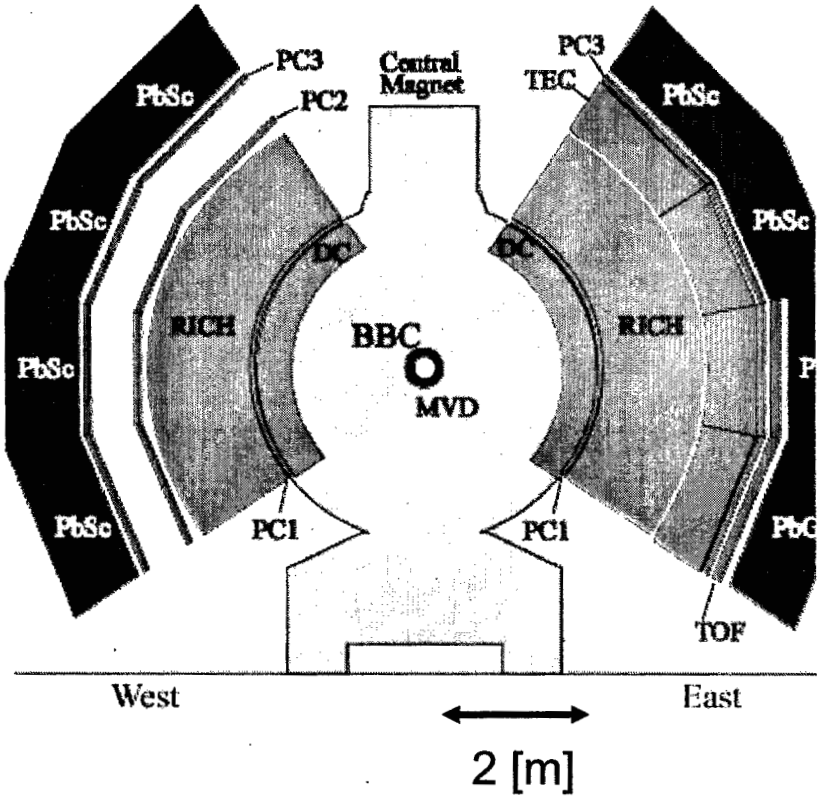
RHIC run3 p+p

2003 April-May
$\sqrt{s}$=200GeV Proton-proton collisions
Luminosity= 240nb^{-1}

RHIC-PHENIX detector

Central Arm (West)
(Rapidity |y|<0.35)
Electromagnetic Calorimeter (EMCal)
Photon detection
High granularity (~10*10mrad^2)
Drift chamber (DC)
Charged hadron veto
Beam forward / backward
(Rapidity 3.1<|y|<3.9)
Beam-beam counter (BBC)
Triggering and vertex determination
Luminosity measurement

BBC and EMCal Trigger for the data taking



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Analysis Strategy

Photon cluster selection

—Photon shape cut (important to remove merged π^0 clusters)
—Charged veto with DC track
—Timing cut

π^0 photon tag

—Count photons with π^0 partner
—Estimate π^0 photons without partner
(it is only kinematics and geometrical issue)

Other hadron to photon estimation (η,ω, etc.)

—Scale π^0 photon contribution by their production and branching ratio

The rest is our direct photon signal !! **(Subtraction method)**

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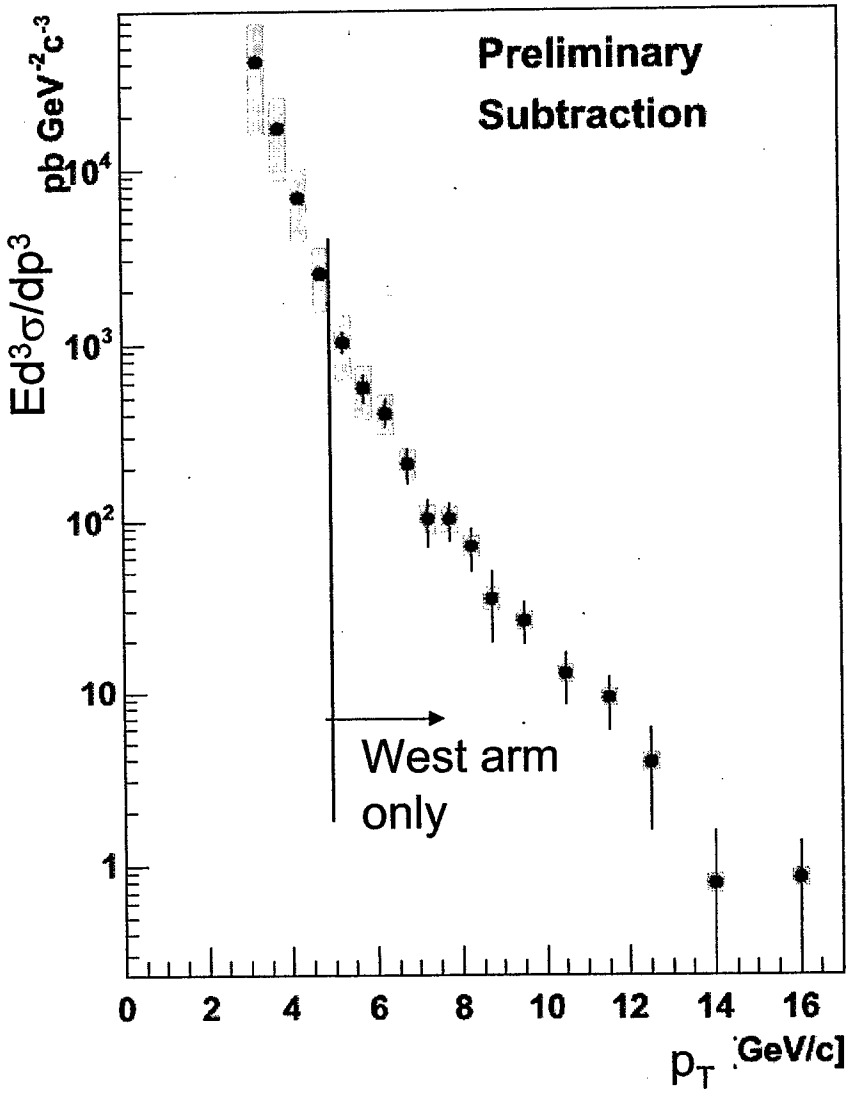
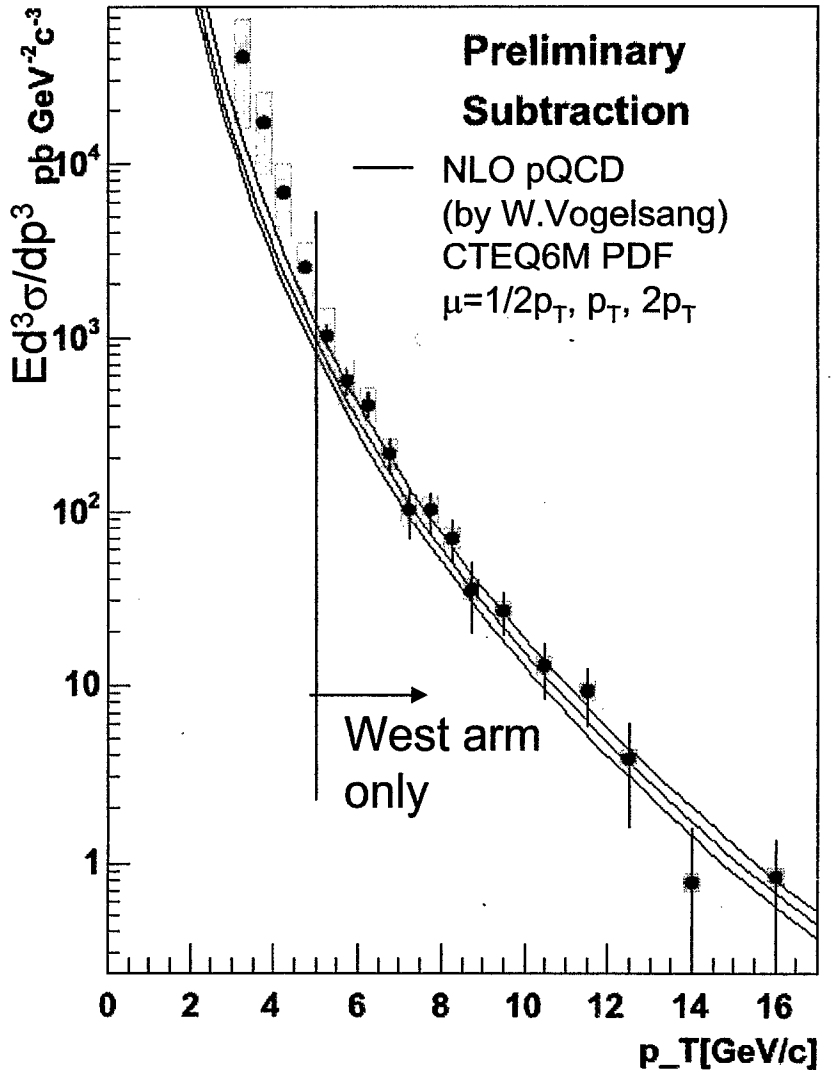
Subtraction method



Systematic error sources ✓ ✓ ✓ ✓

	pT region Low	Mid	High
Luminosity	✓	✓	✓
Energy scale	✓	✓	✓
Non photon BG	✓		
Pi0 tag	✓	✓	
Missing π^0	✓	✓	
Non π^0 photon	✓	✓	

Subtraction method



NLO pQCD calculation explains the data well.

At low pT, the data show an excess.

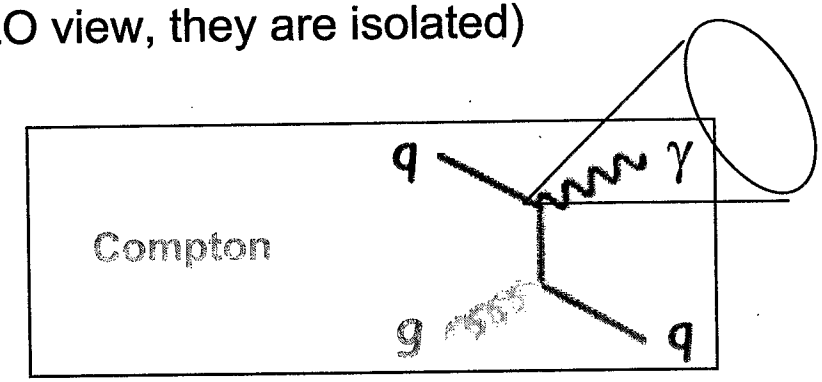
—with large systematic error

—but may be soft physics contributions as well

Isolation cut method : 2 goals

1

— Check if our direct photon signal is isolated.
(with LO view, they are isolated)



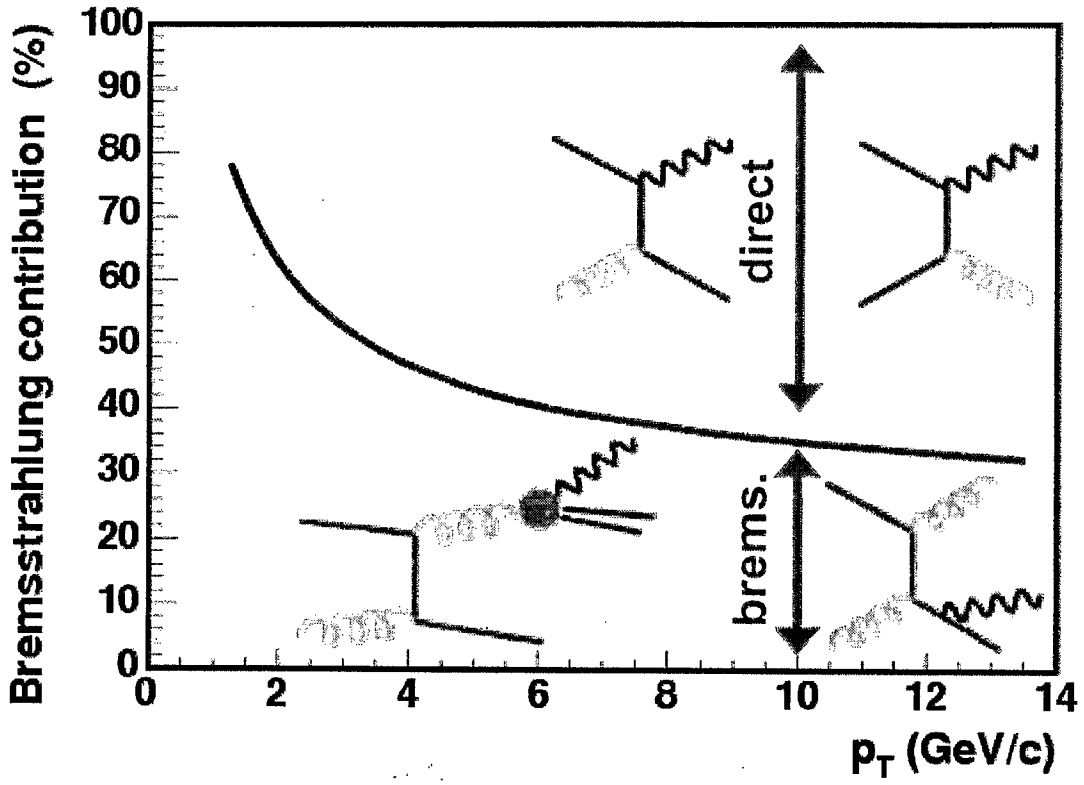
— A confirmation is done by applying the same isolation cut on photons from π^0

Isolation cut method : 2 goals

2

Can we extract contribution of direct production?

NLO pQCD calculation by W. Vogelsang (p+p at √s=200 GeV)



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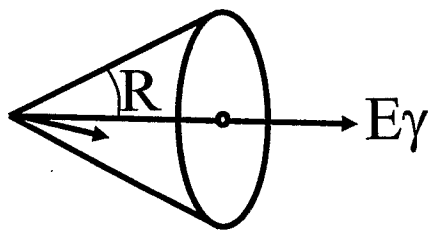
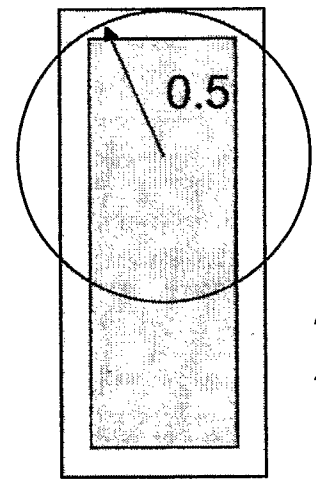
Isolation cut with PHENIX

- Starting from isolated photons

$0.1E\gamma > E_{cone}$ (R=0.5rad)



E_{cone} : photon energy
+ charged particle momentum

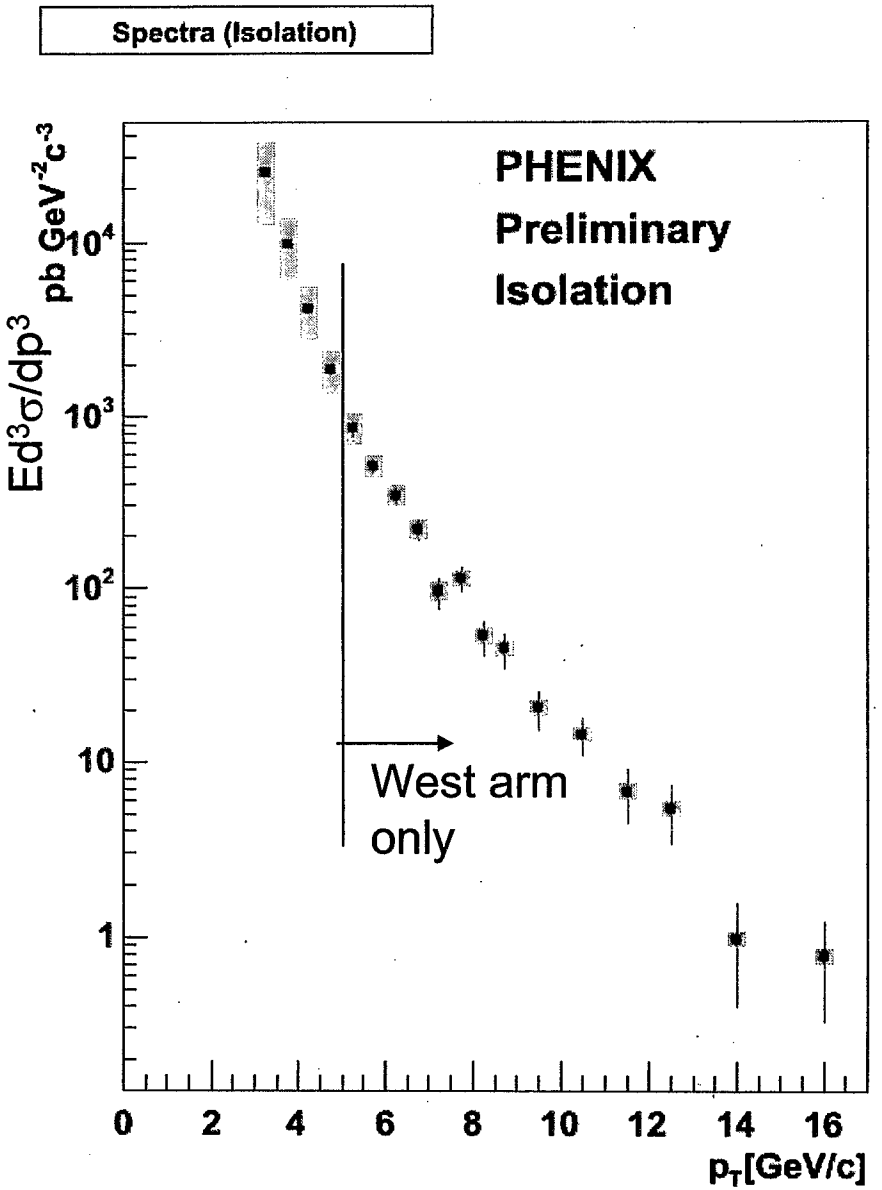


PHENIX arm
$\Delta\eta=0.7$
$\Delta\phi=\pi/2$

- For the estimation of hadron contribution,

"Isolated π^0 photon" is introduced
They have π^0 partner.
They pass the isolation cut when the partner energy is excluded.

Isolation cut method



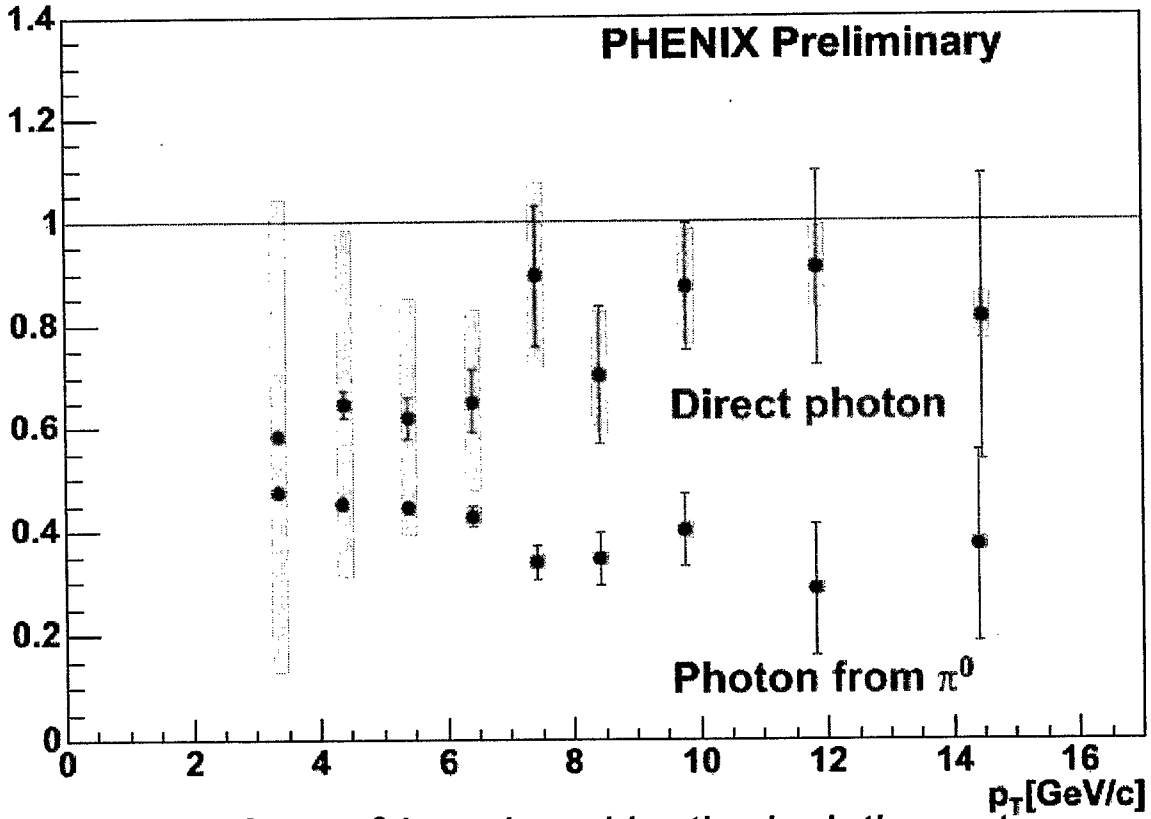
Isolation cut

$0.1*E\gamma > E_{cone(R=0.5rad)}$

No correction for isolation cut efficienc
was applied.

Ratios

1 Direct photon : isolation / subtraction
Photon from π^0 : isolated photon / all

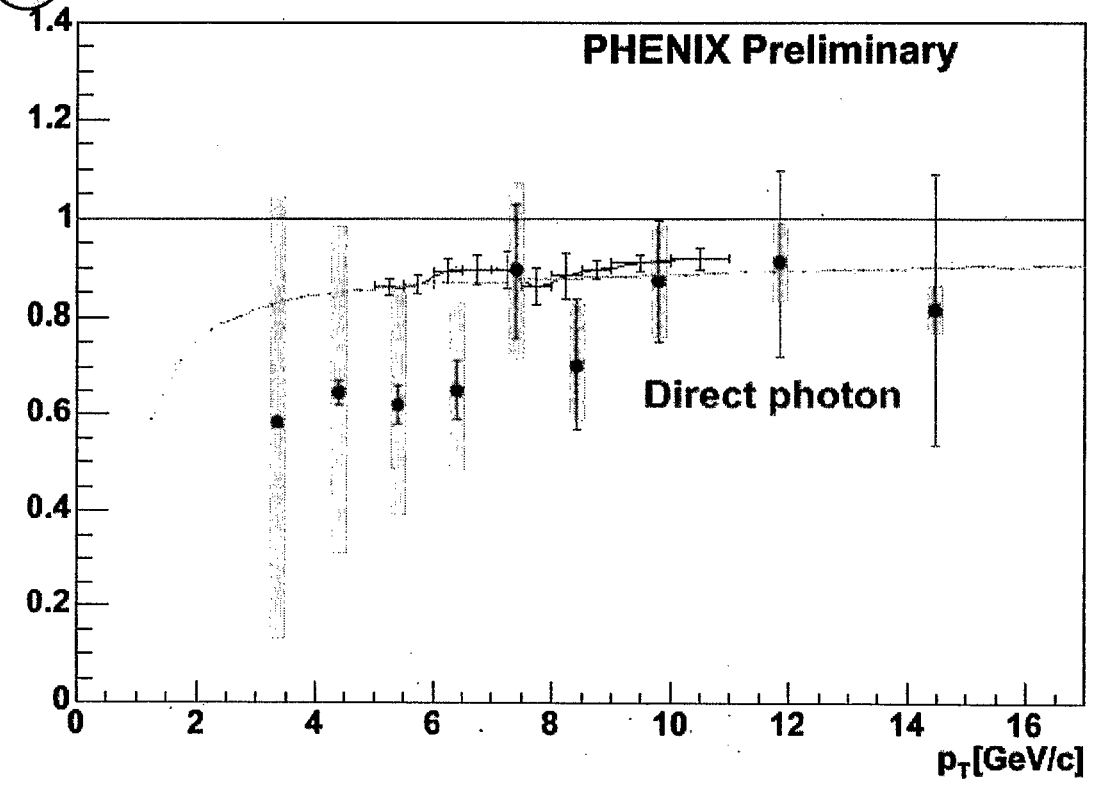


Isolation cut
$0.1*E\gamma > E_{cone(R=0.5rad}$

Photons from π^0 is reduced by the isolation cut.
Direct photons are clearly isolated at high pT region.

Iso/sub ratio with a theory calculation

2



Isolation cut
$0.1*E\gamma > E_{cone(R=0.5rad)}$

By M.Werlen,
JETPHOX
-.35<y<.35
μ=pT
BFG set2, CTEQ6M

By W.Vogelsang,
R=0.4
μ=pT, CTEQ6M

At high pT, theory predictions are consistent with the data.

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Prospects for Δg measurement

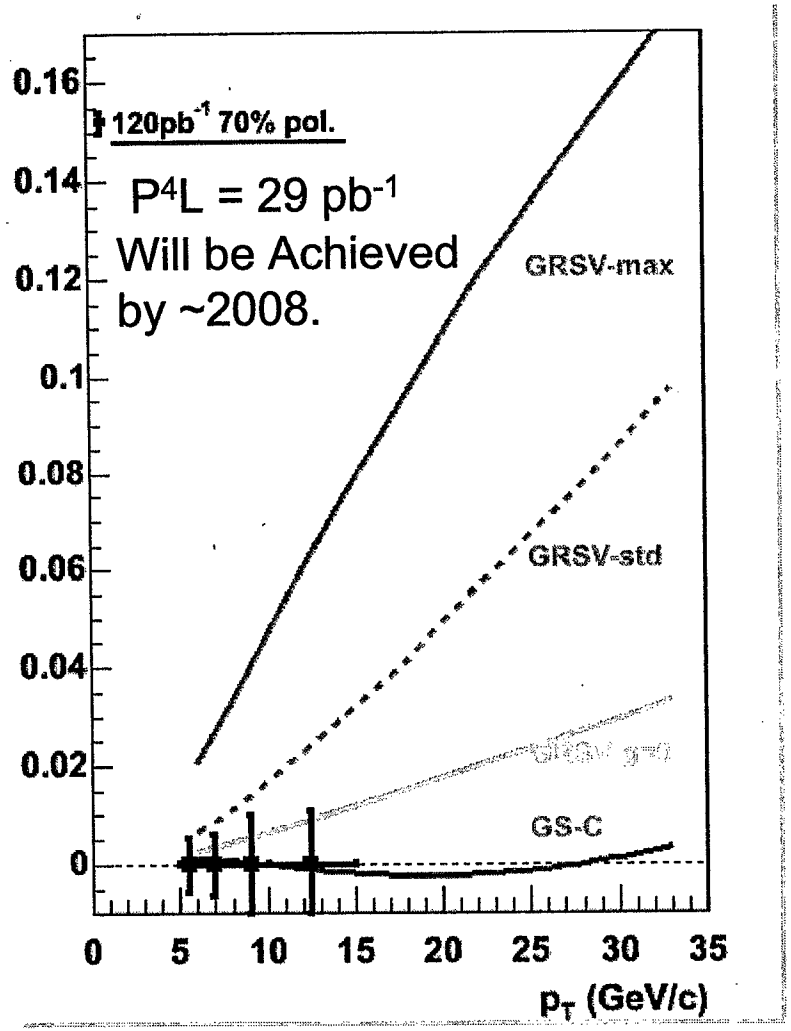
For the asymmetry measurements, the purity is important.

dA_{LL}_signal= D * dA_{LL}_allphoton
1/D: purity (=signal/all)

☺ With the isolation cut, the purity is about 80% for pT>10GeV/c.
And most direct photons remains.

In Run5, we took ~3.5pb^{-1} with 50% pol.
(The figure of merit (P^4L) = 0.22 pb^{-1})

We need a little more luminosity and polarization for photon A_{LL}.



Summary

We are preparing for publication.

Spin Dependent Fragmentation Function Results from Belle

Matthias Grosse Perdekamp

Spin Dependent Fragmentation Function Results from Belle

RBRC Review

October 10th – October 12th, BNL

D. Gabbert (University of Illinois and RBRC)
M. Grosse Perdekamp (RBRC and University of Illinois)
K. Hasuko (RIKEN/RBRC)
S. Lange (Frankfurt University/RBRC)
D. Layton (University of Illinois)
A. Ogawa (BNL/RBRC)
R. Seidl* (University of Illinois and RBRC)
V. Siegle (RBRC)

*active group members

Spin Dependent Fragmentation Functions

- The Collins Fragmentation Function
- Why is it interesting to measure the Collins FF?
- The Belle Experiment
- Collins Asymmetries: First Results
- Outlook

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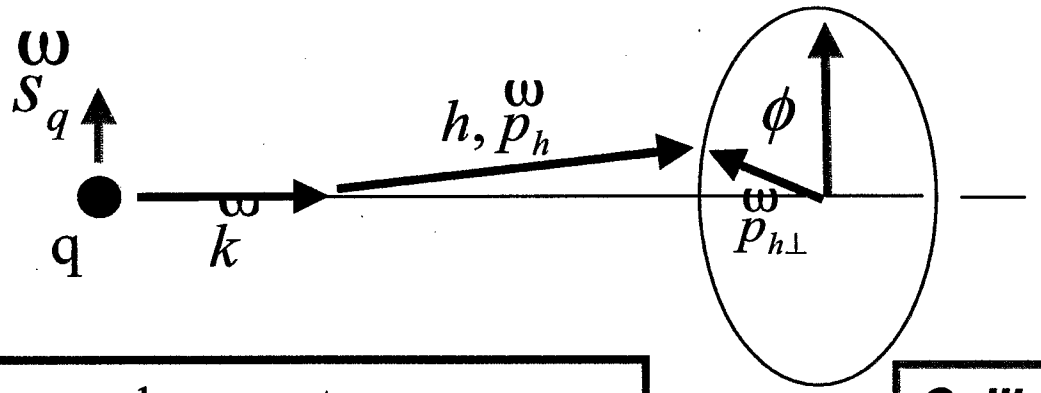
Collins Effect in Quark Fragmentation

J.C. Collins, Nucl. Phys. B396, 161(1993) and
J.C. Collins, S. Heppelmann, G. Ladinsky Nucl.Phys.B420:565-582,1994



$\vec{k}$: quark momentum

$\vec{s}_q$: quark spin

$\vec{p}_h$: hadron momentum

$\vec{p}_{h\perp}$: transverse hadron momentum

$z_h = E_h / E_q$

$= 2E_h / \sqrt{s}$: relative hadron momentum

Collins Effect:
Fragmentation of a transversely polarized quark *q* into spin-less hadron *h* carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

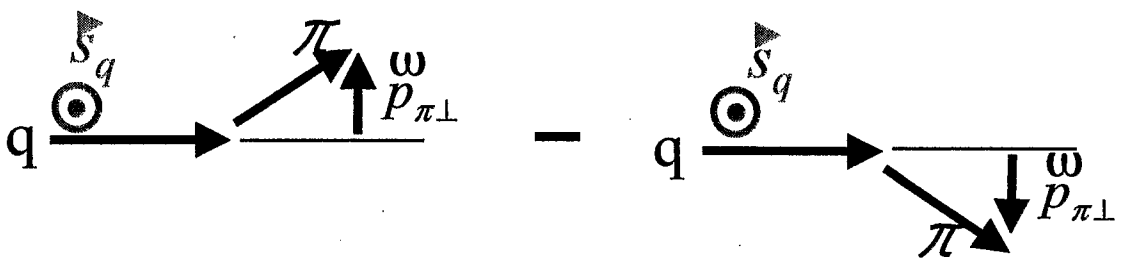
$$\propto \sin\phi$$

Example: Left–Right Asymmetry in Pion Rates

Collins Effect

$$A_T = \frac{N_L - N_R}{N_L + N_R} \neq 0\,!$$

N_L : pions to the left



N_R : pions to the right

General Form for Fragmentation Functions

Number density for finding
a spin-less hadron h from a
transversely polarized quark, q:

$$D^{h}_{q^{\uparrow}}(z, \vec{p}_{h\perp}) = \underbrace{D_1^{q,h}(z)}_{\textbf{unpolarized FF}} + \underbrace{H_1^{\perp q,h}(z, p_{h\perp}^2)}_{\textbf{Collins FF}} \frac{\left(\hat{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q}{zM_h}$$

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Why is the Collins Fragmentation Function Interesting?

- o Important test case for QCD
- o Interesting symmetry properties
- o Tests of universality and factorization between e+e-, DIS and p-p collisions
- o Connection between microscopic and macroscopic observables:

➔ Probe/analyzer for transverse quark spin critical input for transverse proton spin program at DESY, CERN, JLab and RHIC

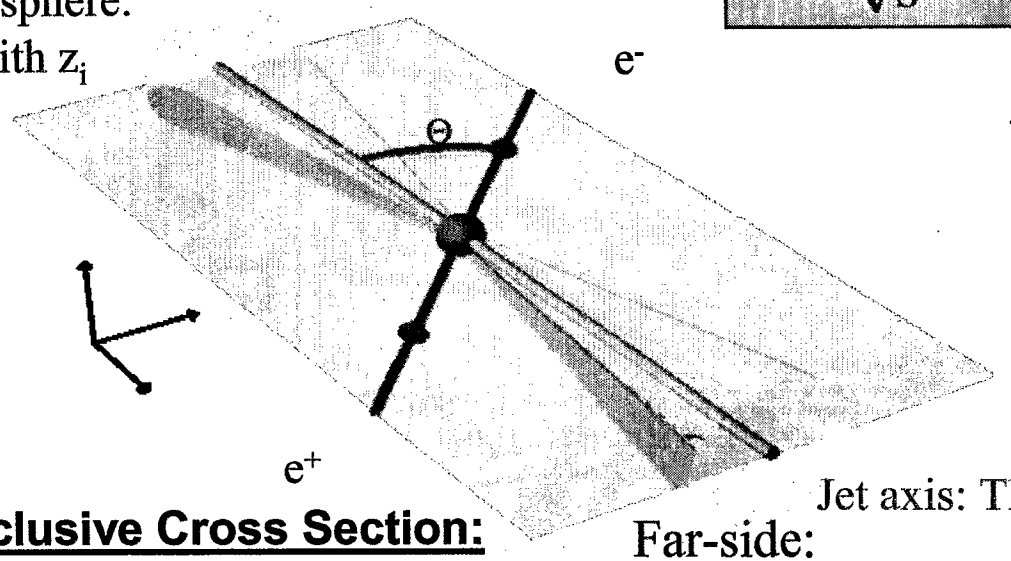
Event Structure in e+e− at Belle

e^+e^- CMS frame:

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\ GeV$$

Near-side Hemisphere:

h_i, $i=1,N_n$ with z_i



$\langle N_{h+,-} \rangle = 6.4$

Jet axis: Thrust

Far-side:

h_j, $j=1,N_f$ with z_j

Spin averaged Inclusive Cross Section:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2} = \frac{3\alpha^2}{Q^2} A(y) \sum_{a,\bar{a}} e_a^2 D_1(z_1) \bar{D}_1(z_2)$$

$$A(y) = \left(\frac{1}{2} - y + y^2\right) \overset{(cm)}{=} \frac{1}{4}\left(1 + \cos^2\Theta\right)$$

Collins FF in e+e− : Correlation between Hemispheres !

- Quark spin direction unknown: measurement of Collins function in one hemisphere is not possible $\sin\varphi$ modulation will average out!

- Correlation between two hemispheres with $\sin\varphi_i$ Collins single spin asymmetries results in $\cos(\varphi_1+\varphi_2)$ modulation of the observed di-hadron yield.

- Fraction of sample with anti-parallel quark- and anti-quark spin direction $\sim \sin^2\theta$ (assuming negligible beam polarization)

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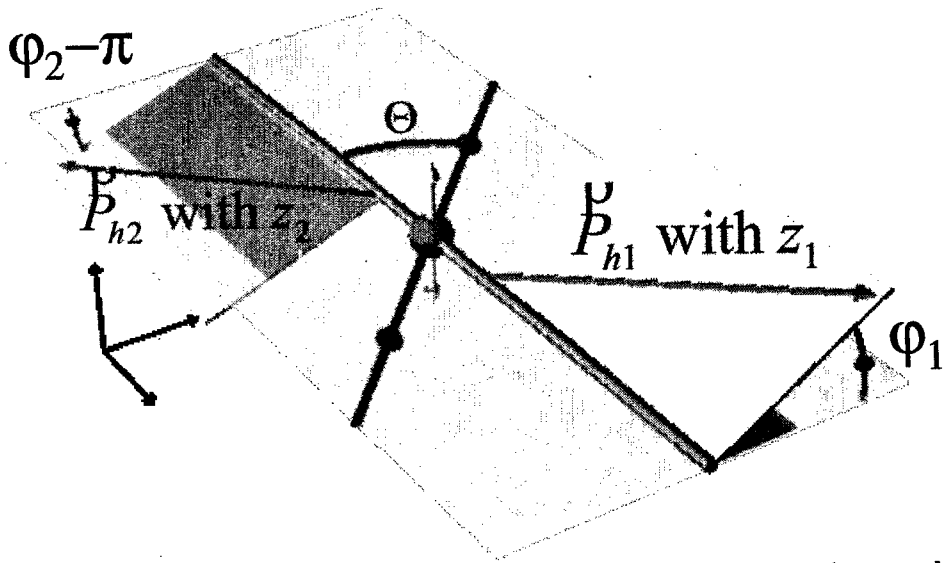
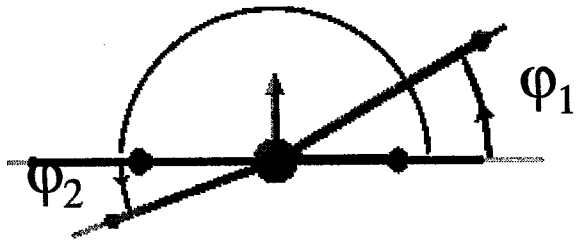
Collins FF: Angles and Cross Section for the $cos(\phi_1+\phi_2)$ Method





2-hadron inclusive transverse momentum dependent Cross Section:

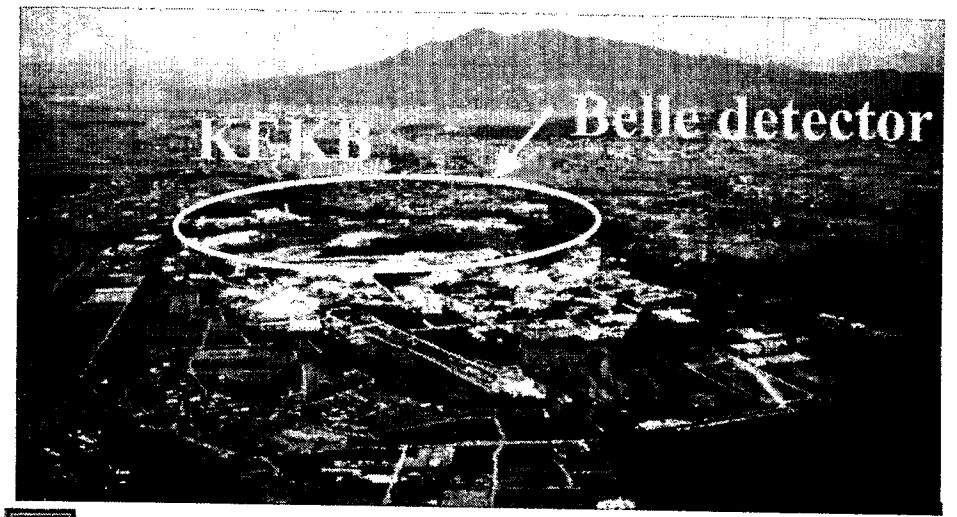
$$\frac{d\sigma(e^+e^- \to h_1h_2X)}{d\Omega dz_1 dz_2 d^2\boldsymbol{q}_T} = \Lambda\ B(y) cos\ (\varphi_1+\varphi_2) H_1^{\perp}(z_1)\overline{H}_1^{\perp}(z_2)$$

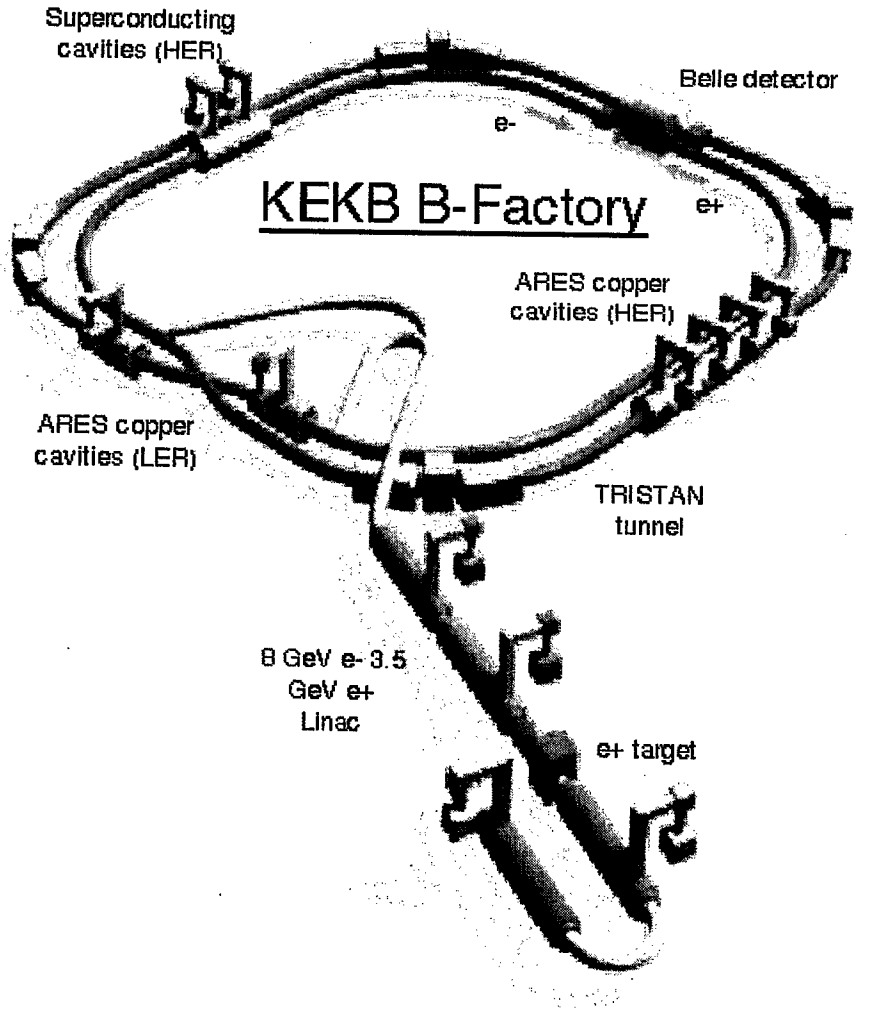
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4} sin^2\Theta$$

Net anti-alignment of Transverse quark spins

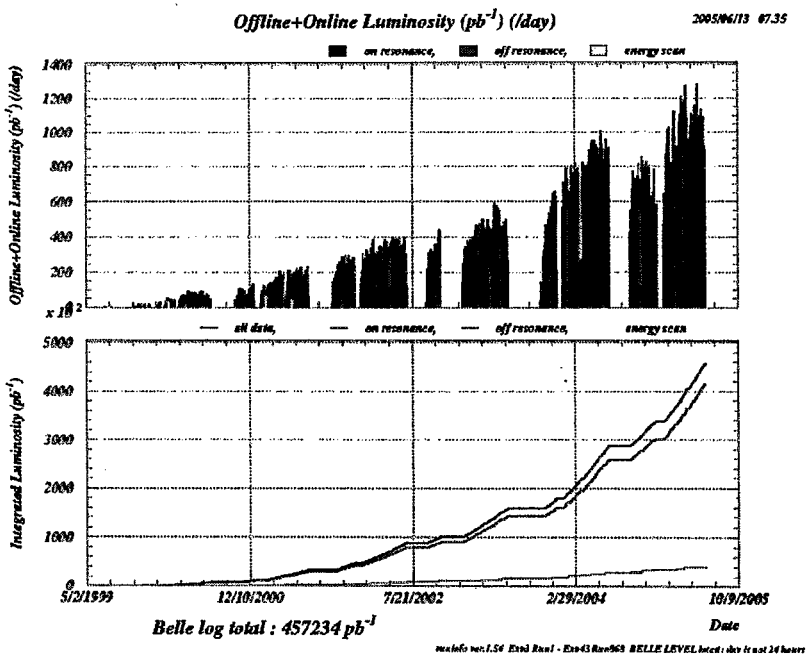
KEKB: $L > 1.5 \times 10^{34} cm^{-2} s^{-1}$!!

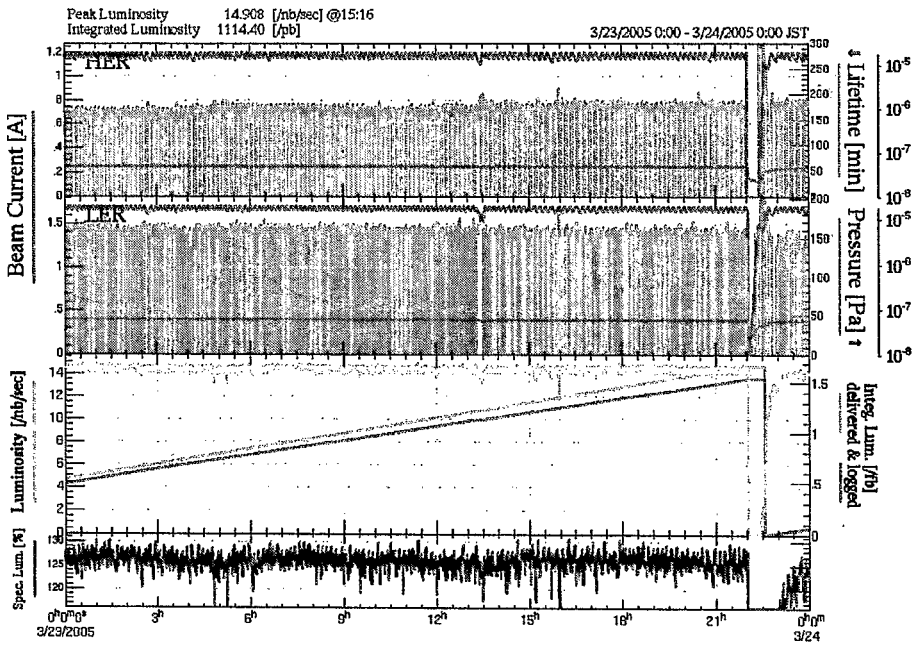
- KEKB
  - Asymmetric collider
  - 8GeV e^- + 3.5GeV e^+
  - $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)
    $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
  - Off-resonance: 10.52 GeV
    $e^+e^- \rightarrow q\ \bar{q}$ (u,d,s,c)
  - **Integrated Luminosity: >400 fb^{-1}**
    >30fb^{-1} => off-resonance



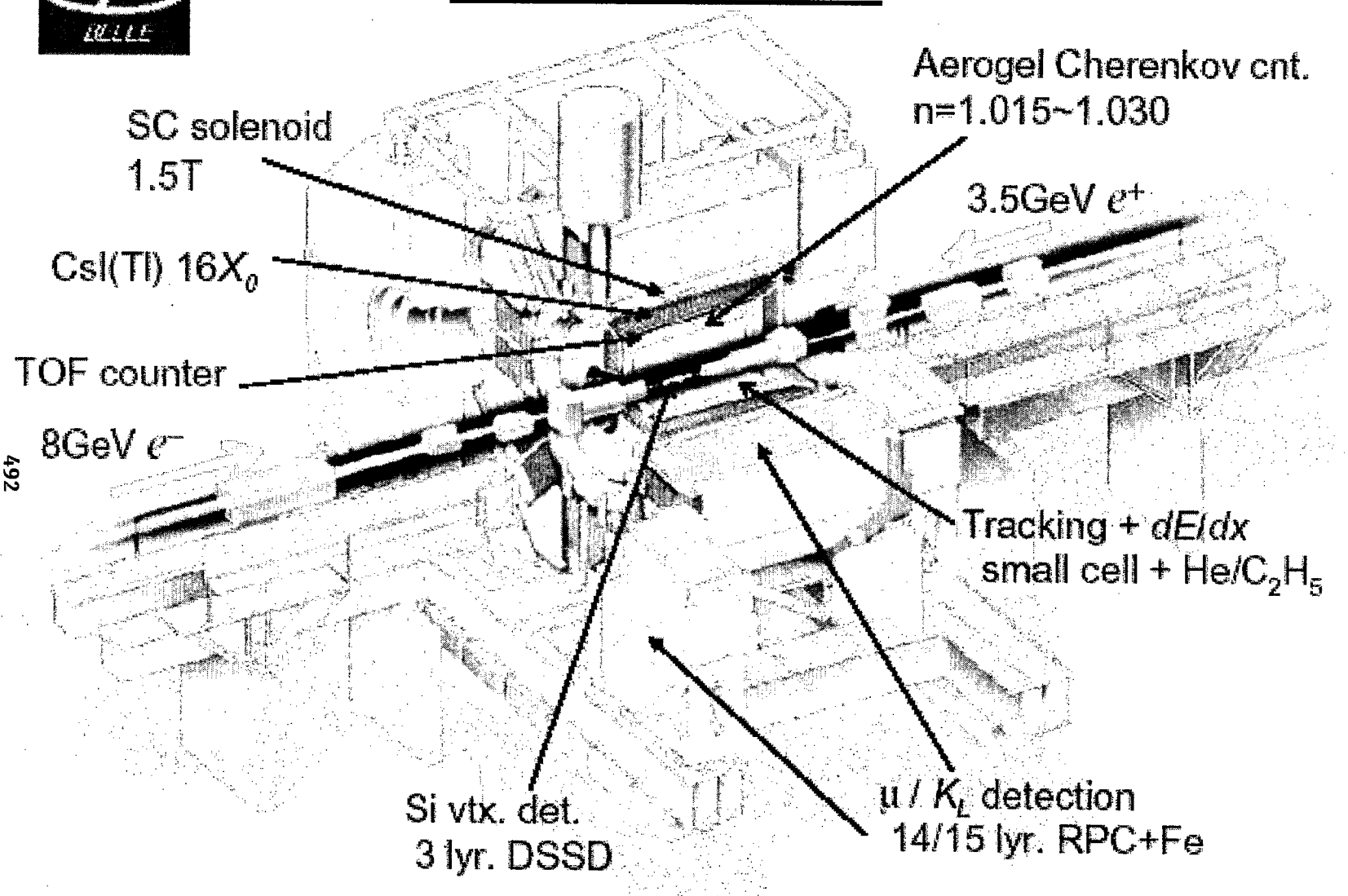


祝 ∫ℒ =400 fb-1 達成
APR-05-2005


Offline+Online Luminosity (pb-1) (/day)
2005/06/13 07:35
on resonance, off resonance, energy scan
Offline+Online Luminosity (pb-1) (/day)
all data, on resonance, off resonance, energy scan
Integrated Luminosity (pb-1)
5/2/1999
12/10/2000
7/21/2002
2/29/2004
10/9/2005
Date
Belle log total : 457234 pb-1

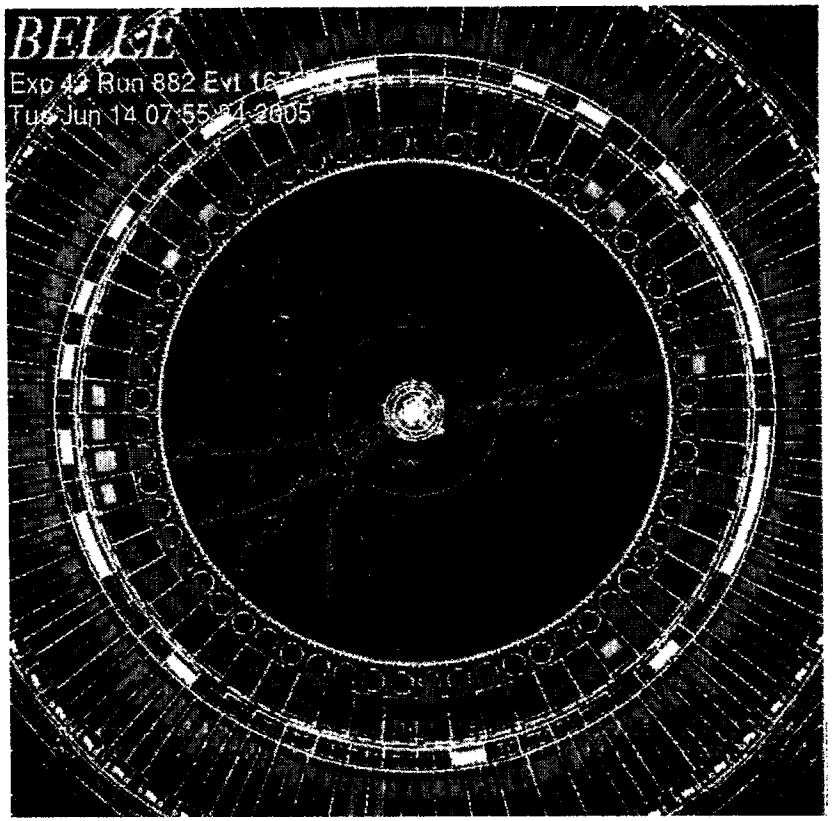

Peak Luminosity 14.908 [/nb/sec] @15:16
Integrated Luminosity 1114.40 [/pb]
3/23/2005 0:00 - 3/24/2005 0:00 JST
HER
LER
Beam Current [A]
Lifetime [min]
Pressure [Pa]
Luminosity [/nb/sec]
Integ. Lum. [/fb] delivered & logged
Spec. Lum. [%]
3/23/2005
3/24

Belle Detector



Good tracking and particle identification!

Typical hadronic events at Belle



~ 1

$$\text{thrust} = \frac{\sum_i p_i \cdot \hat{n}}{\sum_i |p_i|}$$

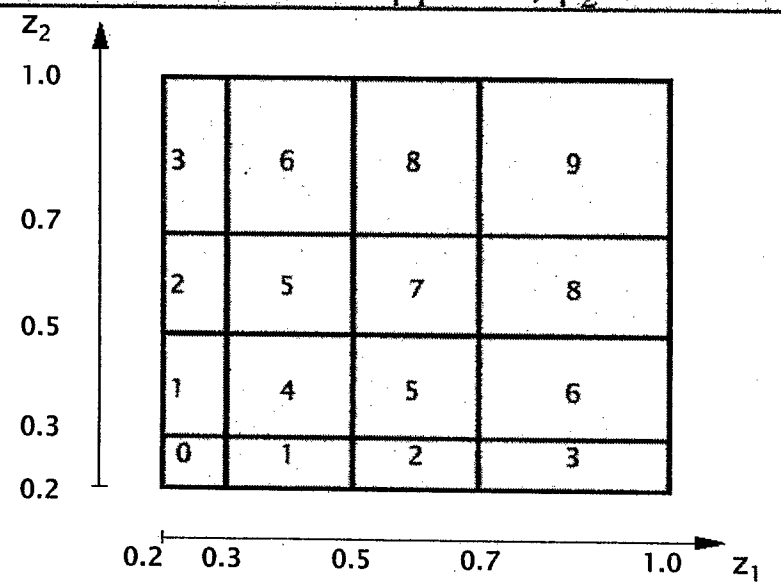
~ 0.5

Applied cuts, binning

- Off-resonance data (in the future also resonance)
- Track selection:
  - pT > 0.1GeV
  - vertex cut: dr<2cm, |dz|<4cm
- Acceptance cut
  - $-0.6 < \cos\theta_i < 0.9$
- Event selection:
  - Ntrack ≥ 3
  - Thrust > 0.8
  - $Z_1, Z_2 > 0.2$

- Light quark selection
- Hemisphere cut

  $(P_{h_2} \cdot \hat{n})\,\hat{n} \cdot (P_{h_1} \cdot \hat{n})\,\hat{n} < 0$
- Opening angle cuts:
  - $\cos(2\phi_0)$ method: $\psi > 120°$
  - $\cos(\phi_1+\phi_2)$ method: $\psi_1 < 60°, \psi_2 > 120°$



z-binning: 0.2 0.3 0.5 0.7 1.0

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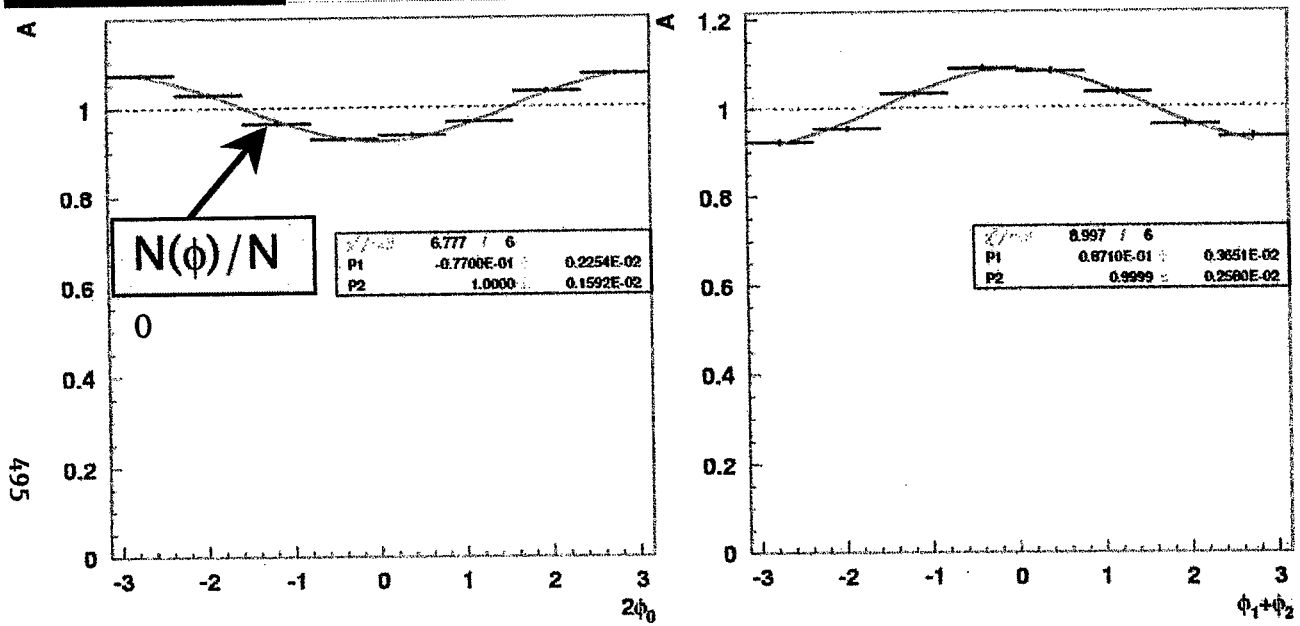
Examples of fitting the azimuthal asymmetries



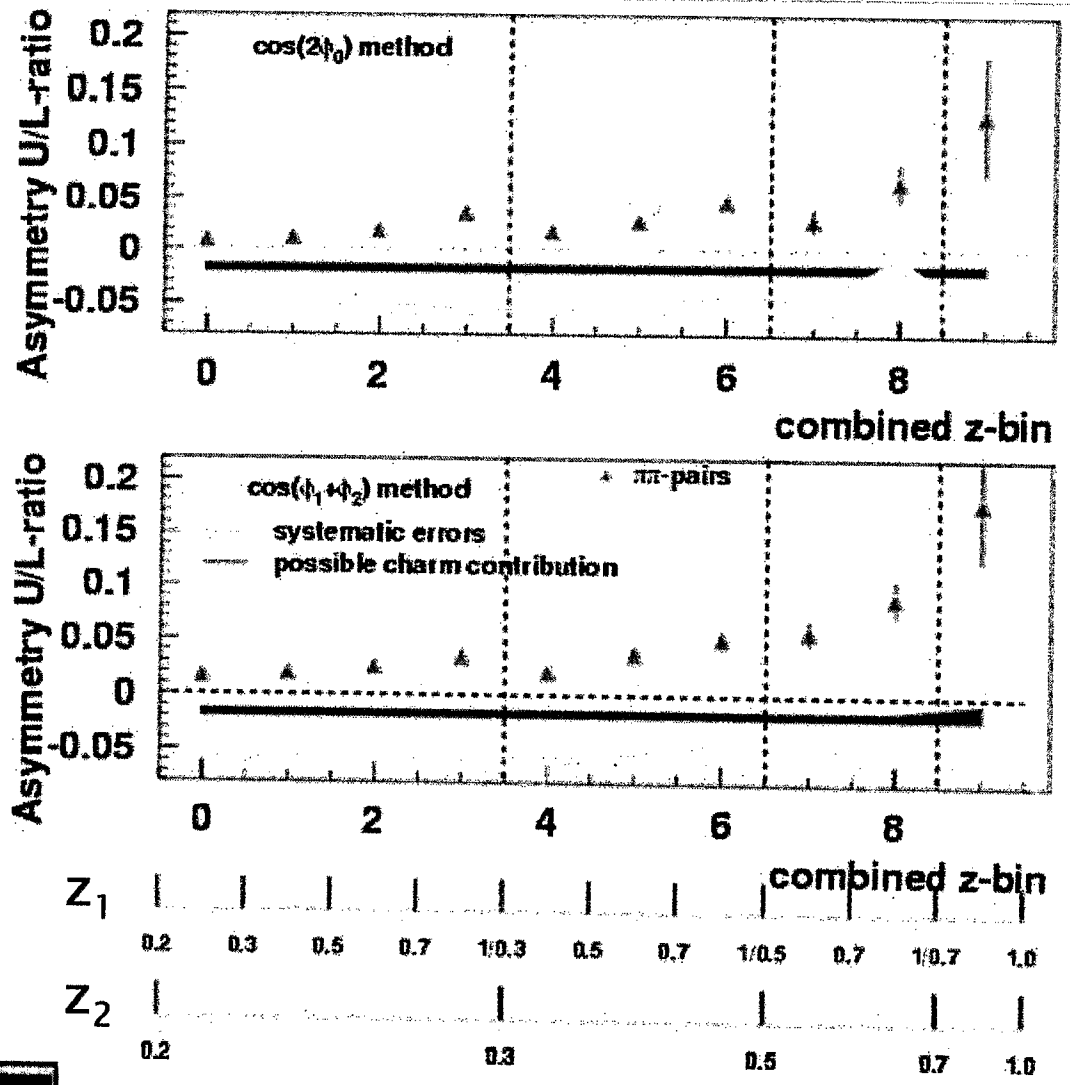
- Cosine modulations clearly visible
- No change in cosine moments when including higher harmonics (even though double ratios will contain them)

$$\frac{N(\phi)}{N_0} = \frac{aD_1\overline{D_1} + cos(2\phi)\left(bH_1\overline{H_1} + cD_1\overline{D_1}\right)}{aD_1\overline{D_1}} = P2 + P1\cos(2\phi)$$

D_1 : spin averaged fragmentation function,

H_1: Collins fragmentation function

Results for π–pairs for $30fb^{-1}$

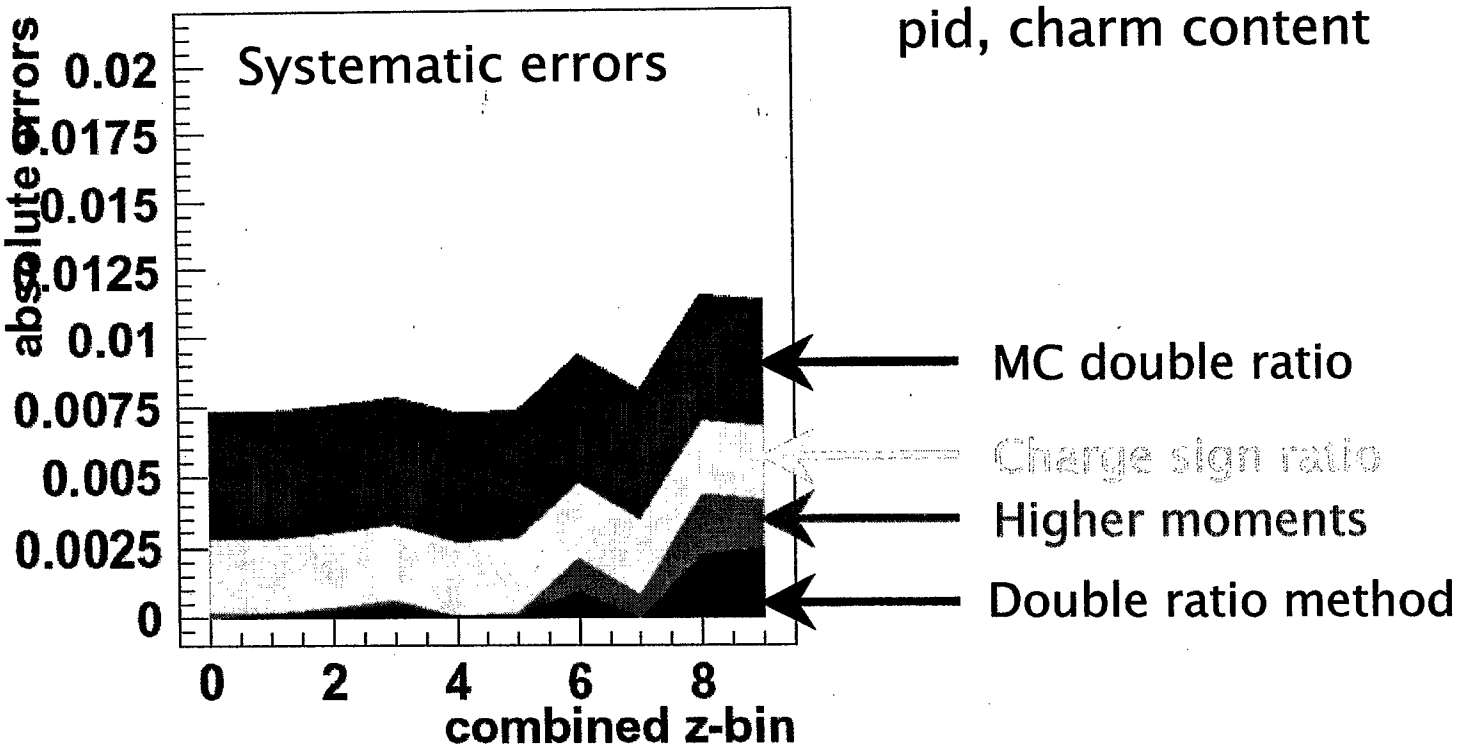


- Significant non–zero asymmetries
- Rising behaviour vs. z
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- First direct measurement of the Collins function

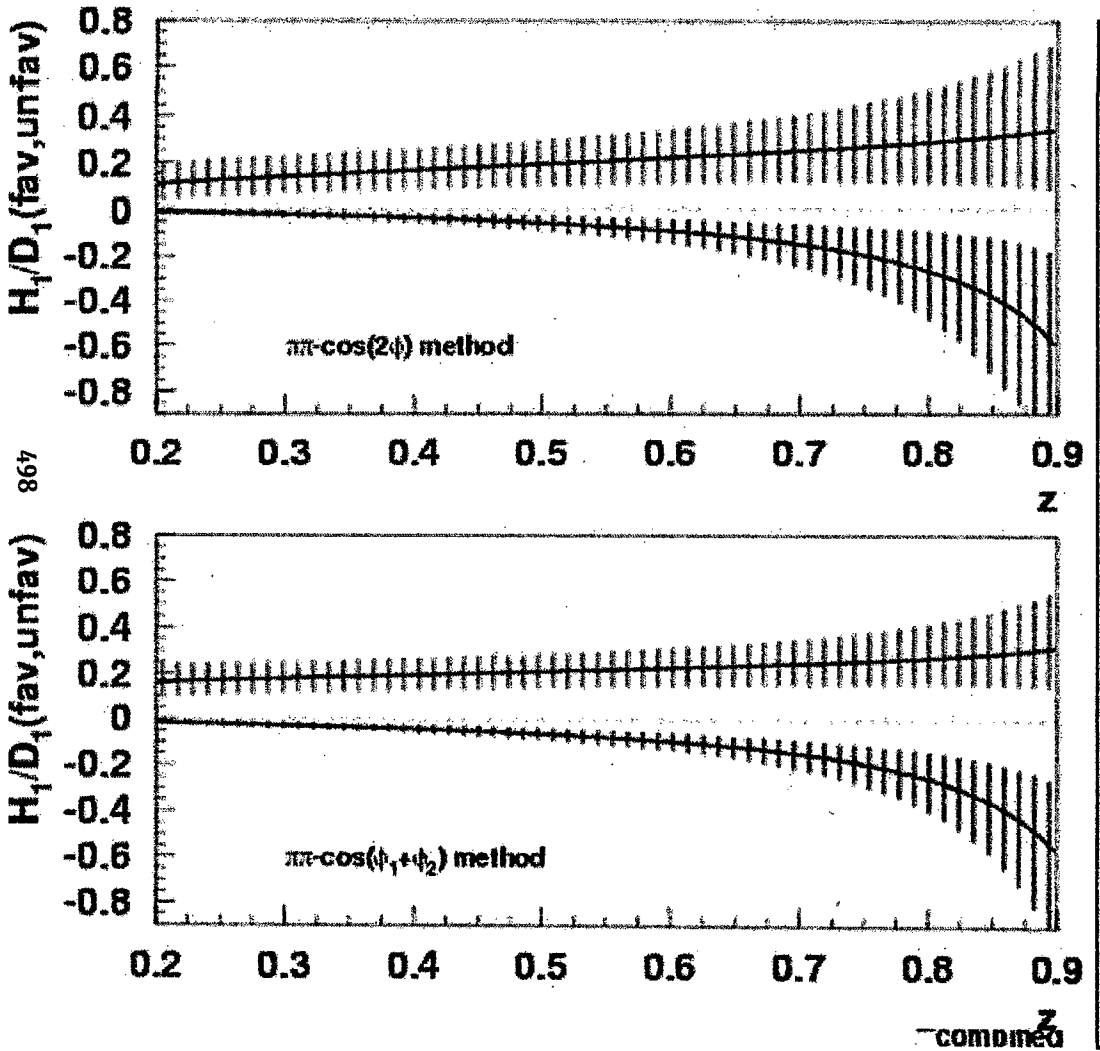
hep-ex/0507063

Systematic errors

Other errors: smearing, pid, charm content



An experimentalist's interpretation: fitting parameterizations of the Collins function(s)



- Take unpolarized parameterizations (Kretzer at $Q^2=2.5\text{GeV}^2$)
- Assume $H_1^{\perp,fav} = a\ z^b\ (1-z)^c$ (PDF-like behaviour)
- Assume $H_1^{\perp,unfav}/H_1^{\perp,fav} = -0.1$
- Sensitivity studies in progress

Summary and outlook

Summary:

- Observation of large azimuthal asymmetries in light quark frag-mentation

  ➔ first measurement of the Collins effect!

- Fundamental interesting + urgently awaited input for the transverse spin physics programs at RHIC but also DESY, CERN and JLab

Outlook:

- (Much) more spin dependent FFs:

  → interference fragmentation
  → Collins FF for VMs
  → Lambdas

- Precision measurement of spin averaged fragmentation func-tions as input to RHIC program to extract the gluon polarization through A_{LL} measurements in in-clusive hadron production

(see appended slides)

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Global Picture: Test Transverse Spin Sum Rule and Fundamental Tensor Charge

RBRC workshop September 2000

SIDIS ⇒
transversity × Collins
transversity × IFF
HERMES, COMPASS,
JLAB, e - RHIC/e - LIC

e^+e^- ⇒ Collins FF
Interference FF
Belle/BABAR

Theory

Transversity
Tensor Charge

+

RBRC

pp ⇒ RHIC/BNL
A_N for inclusive hadrons, A_{TT} in Jets
A_T in Jets : transversity × Collins
transversity × IFF
A_{TT} Drell Yan :
transversity × transversity
BRAHMS, PHENIX, STAR, GSI

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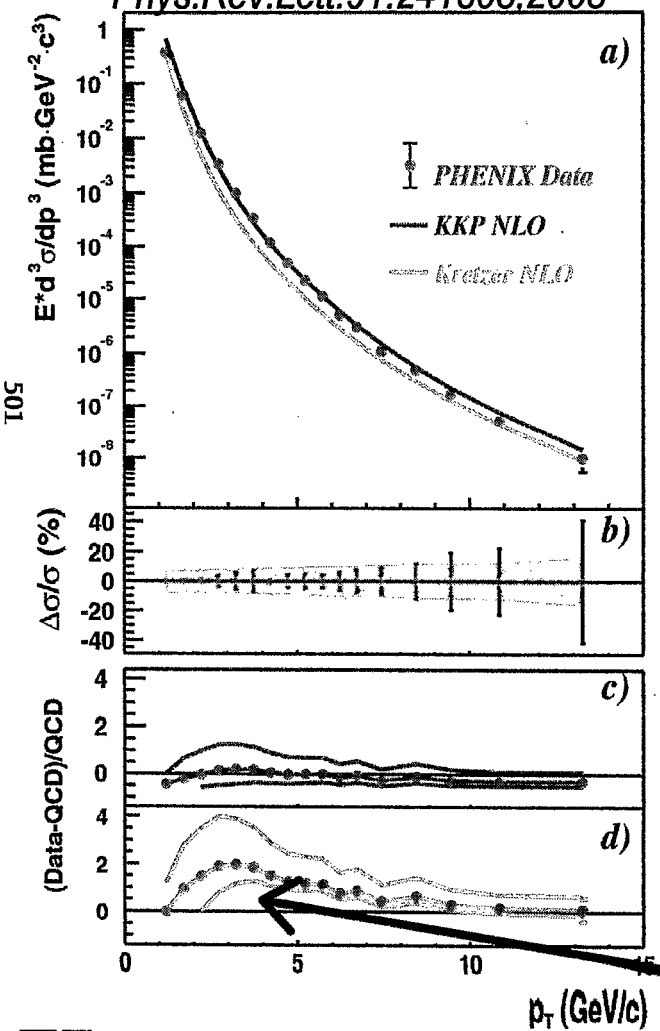
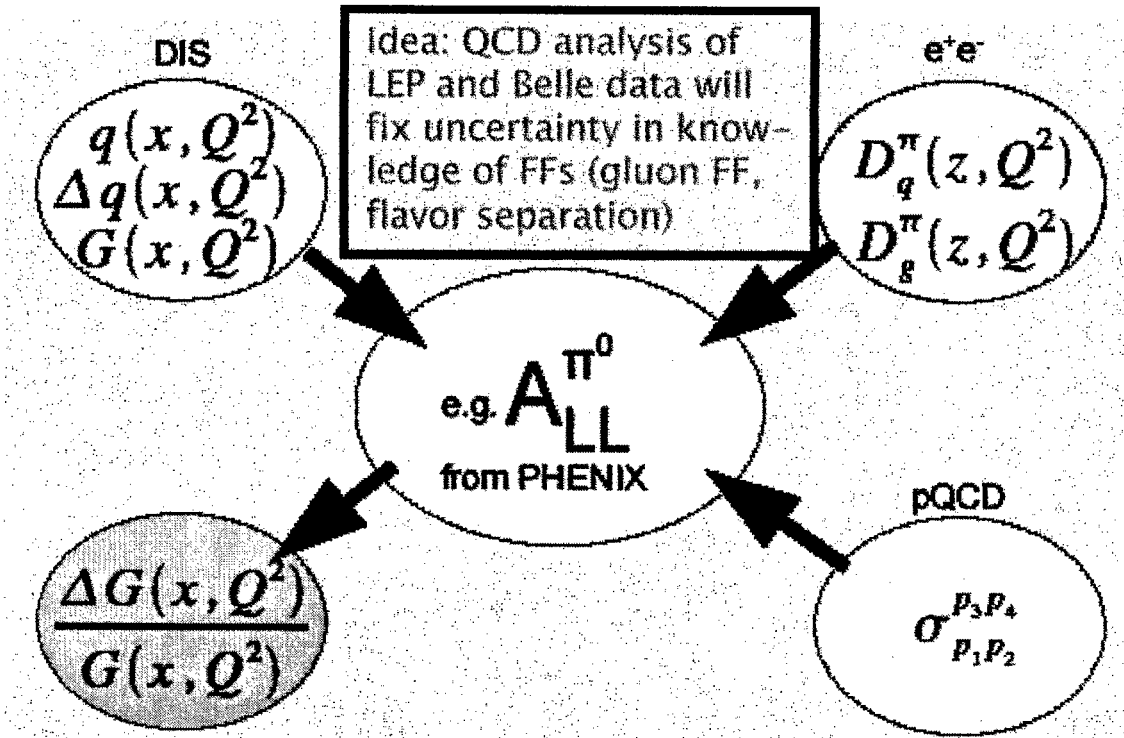
Belle Fragmentation Functions as Input for: ΔG from QCD Analysis of A_{LL}(incl. hadrons)

PHENIX π^0 cross section a $|\eta|<0.35$

Phys.Rev.Lett.91:241803,2003



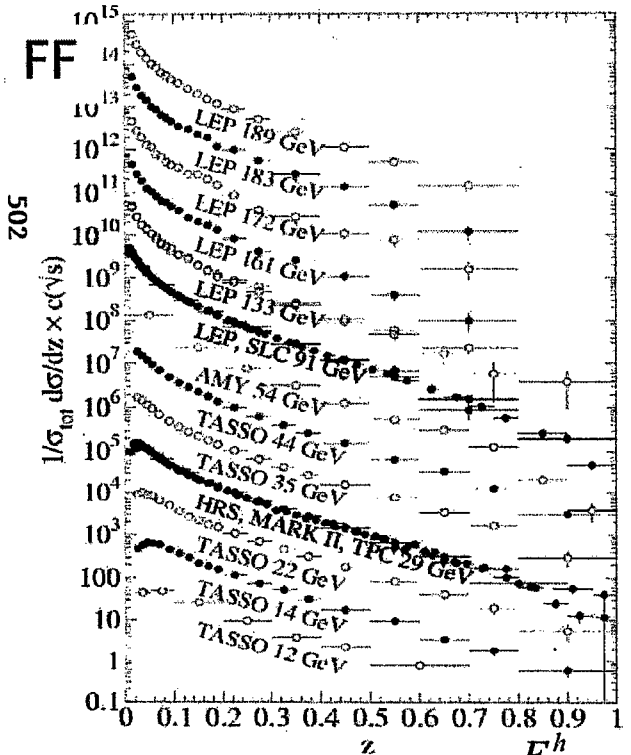


$$A_{LL} \equiv \frac{d\Delta\sigma}{d\sigma} = \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}}$$

Deviation connected to uncertainties in FFs → gluon FF!

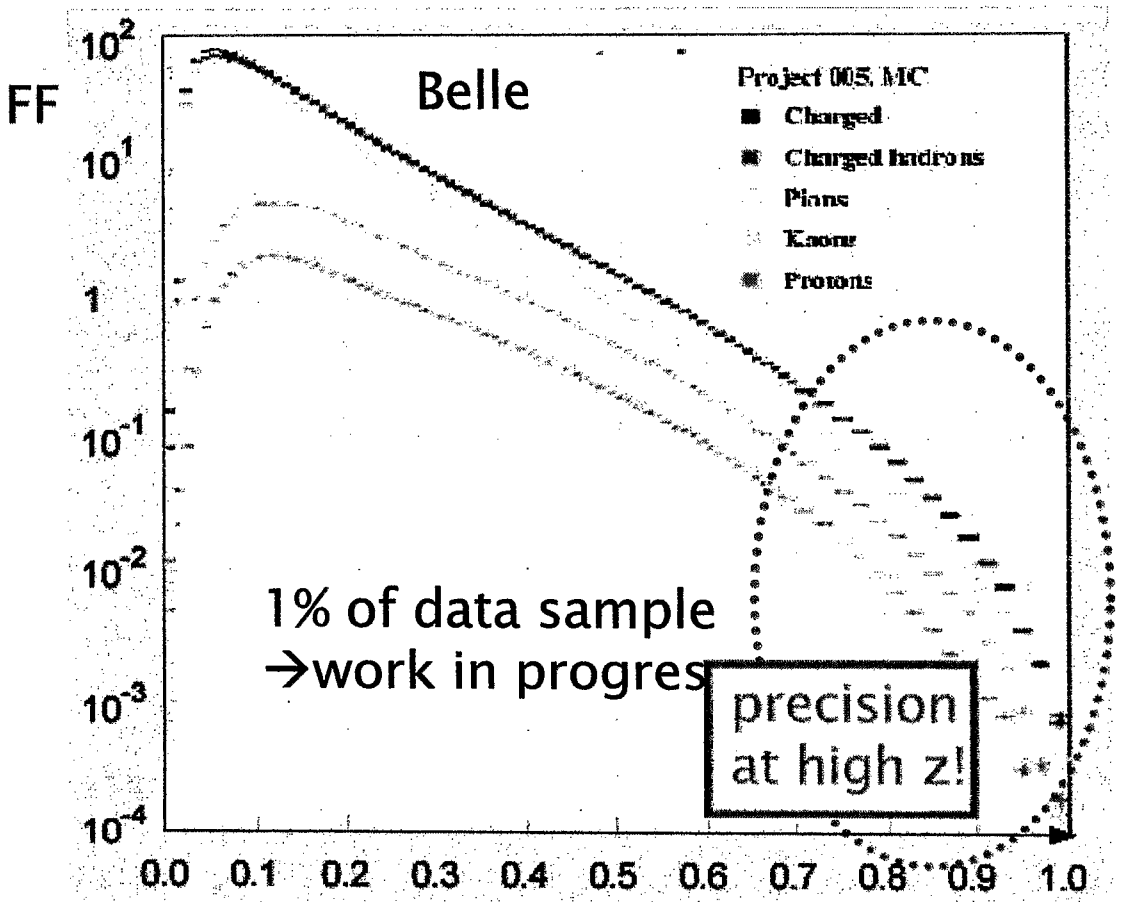
Belle Impact on the Knowledge of FFs

Compelation of data available for the charged hadron FF



$$z = \frac{E^h}{\sqrt{s}/2}$$

Belle: Charged $h^{+/-}$, pions, kaons, protons



$$z = \frac{E^h}{\sqrt{s}/2}$$

Toward Measuring the Internal Spin-Dependent Transverse Momentum of Quarks and Gluons in the Proton at RHIC

Douglas E. Fields

PHENIX

Toward Measuring the Internal Spin-Dependent Transverse Momentum of Quarks and Gluons in the Proton at RHIC

D.E. Fields

University of New Mexico/RBRC

PHENIX

Outline

- Measuring transverse momentum of jets
- Looking for a correlation of this measurement with spin direction
- Initial measurements in Run03
- Status of Run05
- Summary

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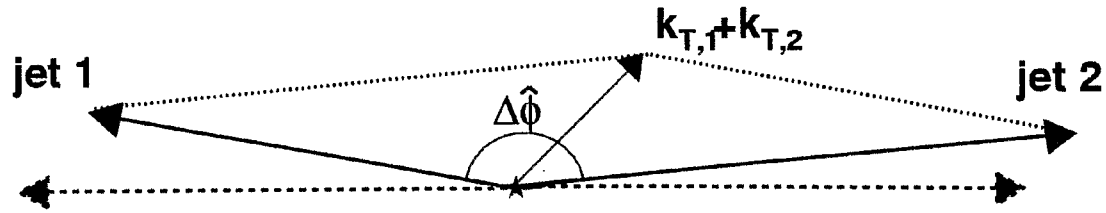
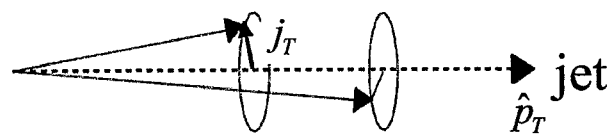
Jet Transverse Momentum, k_T



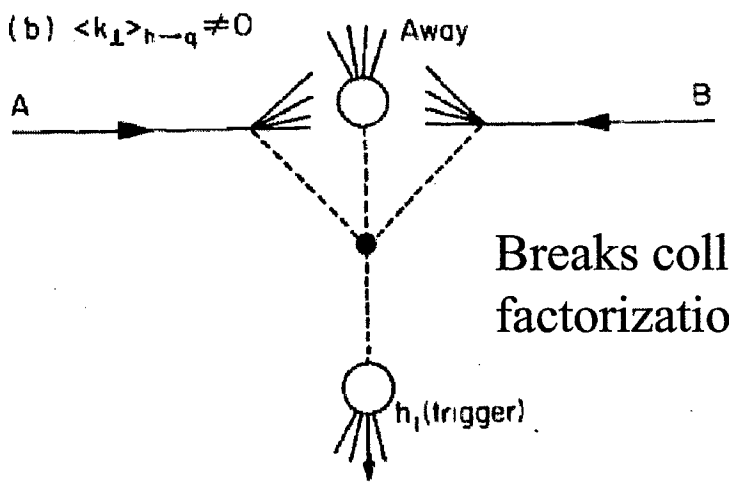
- Back-to-back nature of jets is broken by initial state transverse momentum k_T



- Additionally, if one doesn't measure the jet, but rather the jet fragments (say, the leading particle and correlated particles), the back-to-back nature of these fragments is also broken by the jet fragmentation transverse momentum j_T

Sources of k_T

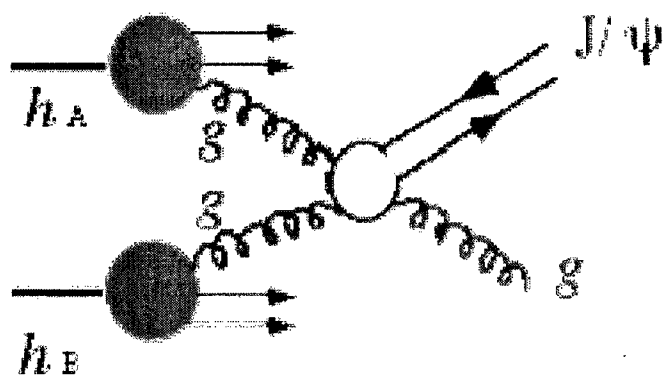
Intrinsic $k_T \approx 200$ MeV/c



Breaks collinear factorization

Soft QCD radiation.

An example - J/ψ production.



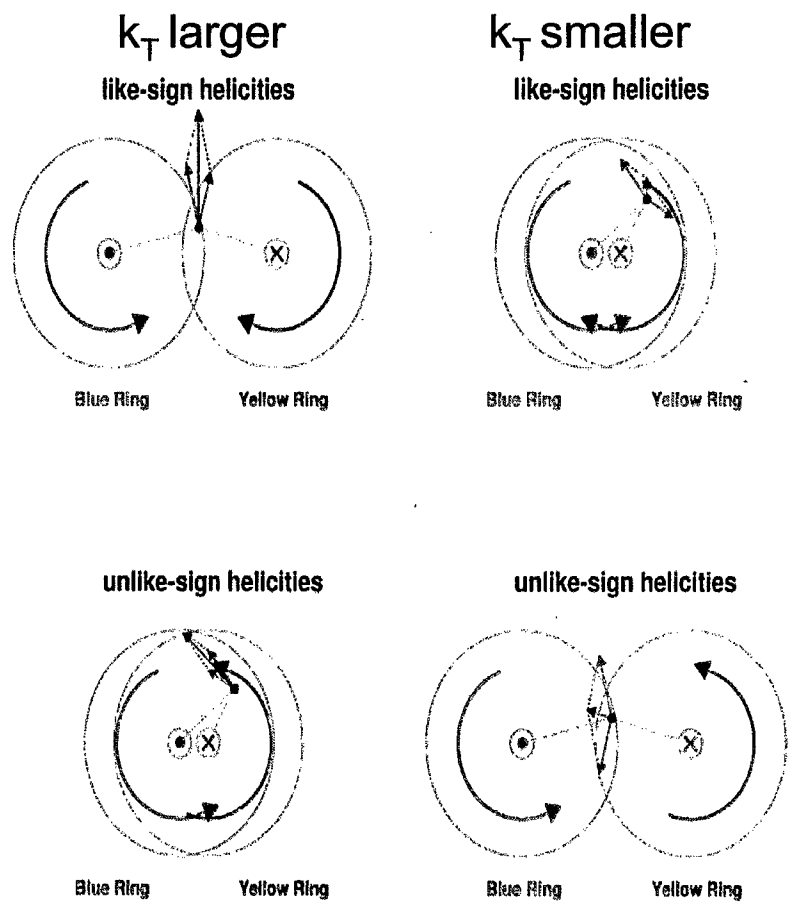
Extra gluon kick

$\langle p_T \rangle_{J/\psi} = 1.8 \pm 0.23 \pm 0.16$ GeV/c

Phys. Rev. Lett. 92, 051802, (2004).

k_T from Orbital Motion

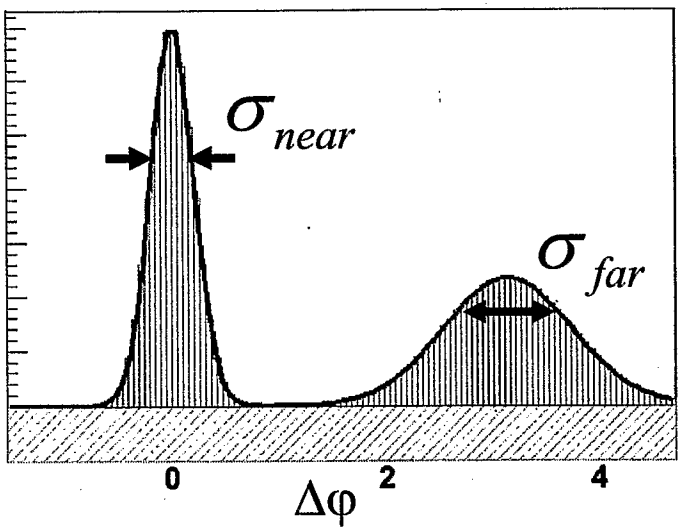
- One can consider the possibility that spin-correlated transverse momentum (orbital angular momentum) may contribute to jet k_T.
  - E.g., Meng Ta-chung et al., *Phys. Rev. D 40 (1989)*

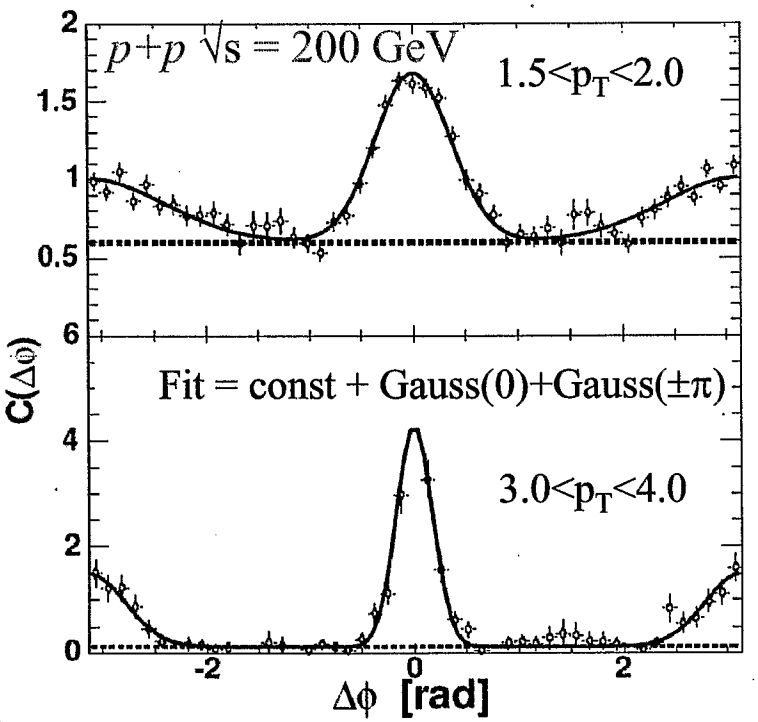


k_T Measurement in PHENIX

$$C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$$

π^0 - $h^{\pm}$ correlation functions



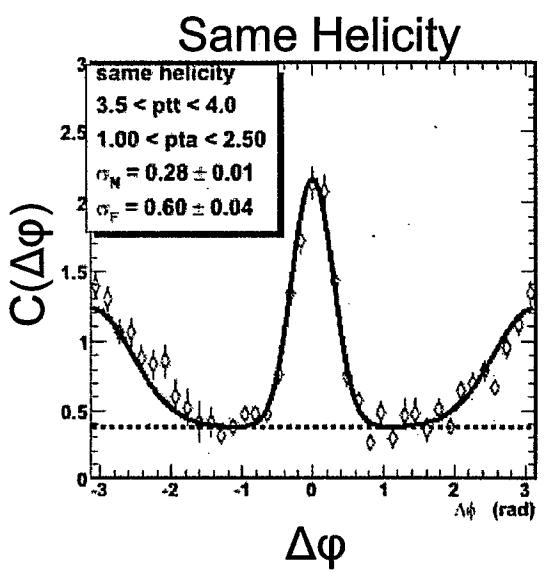


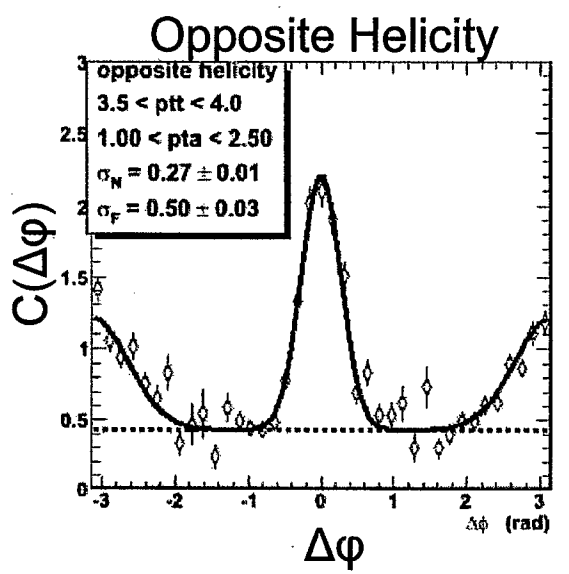
Intra-jet pairs angular width : $\sigma_N \rightarrow \langle j_T \rangle$

Inter-jet pairs angular width : $\sigma_F \rightarrow \langle j_T \rangle \oplus \langle k_T \rangle$

Spin Sorted Analysis

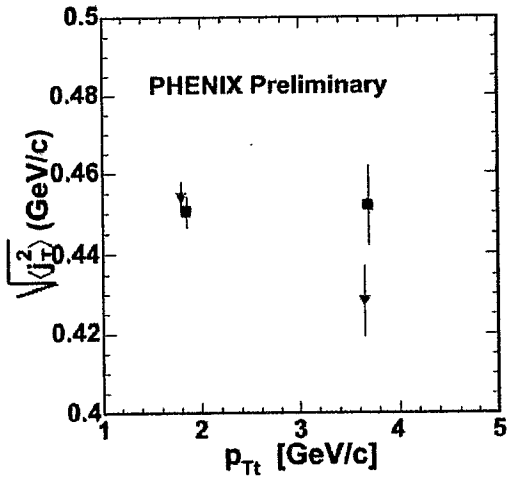
- Do exactly the same analysis sorted on same and opposite helicity bunch crossings, extract $\langle zkt \rangle_{RMS}$ and look at the difference.

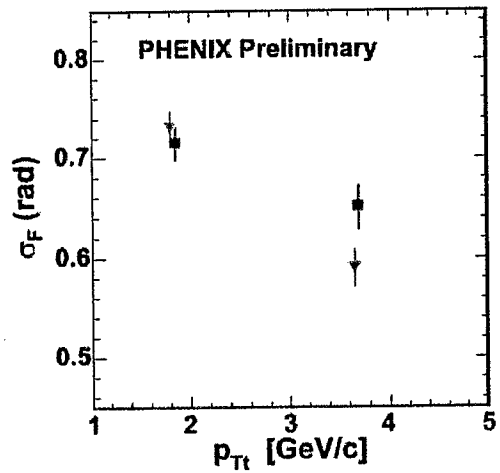




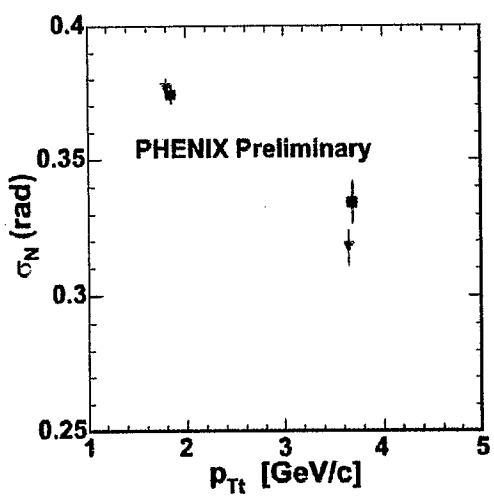
Run03 Data

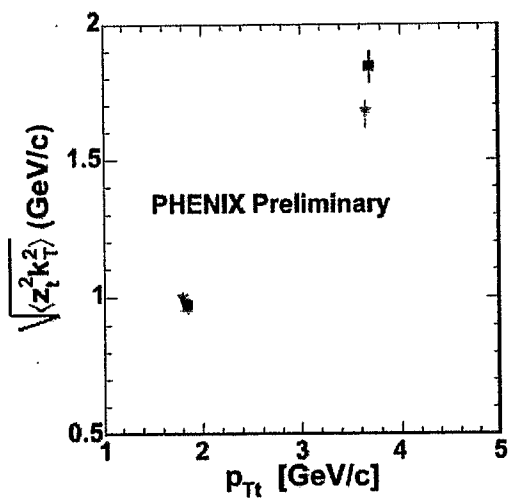
- Run03 data is binned into two bins in trigger particle (π^0) p_{Tt}:
  - $1 GeV/c^2 < p_{Tt} < 3 GeV/c^2$
  - $3 GeV/c^2 < p_{Tt} < 5 GeV/c^2$





$$\sqrt{\langle j_T^2 \rangle} = \langle p_{\perp assoc} \rangle \sin \sigma_N$$





$$\sqrt{\langle z^2 \rangle \langle k_T^2 \rangle} \propto \frac{1}{x_h} \sqrt{\langle p_{out}^2 \rangle - \langle j_{Ty}^2 \rangle (1 + x_h^2)}$$

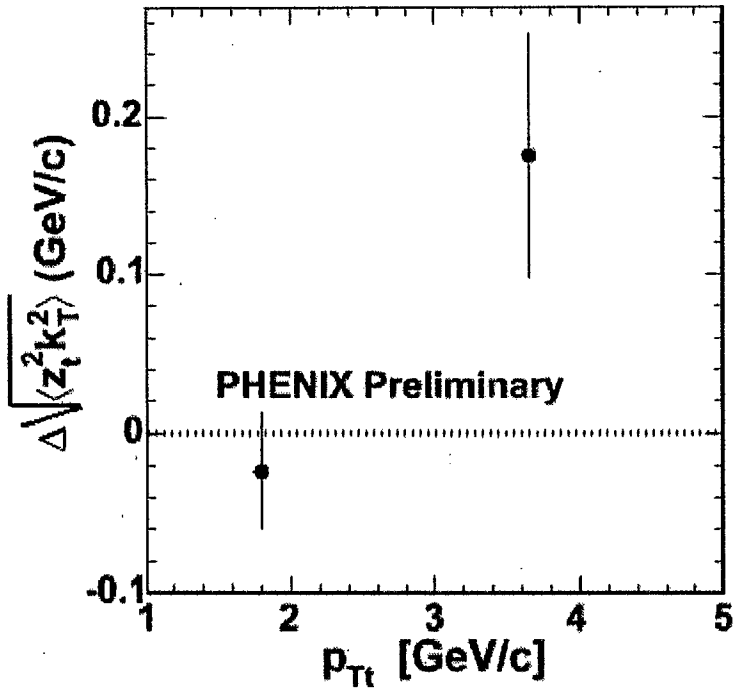
$$p_{out} \propto p_{assoc} \sin \sigma_A$$

$$x_h = \frac{p_{assoc}}{p_{trigg}}$$

512

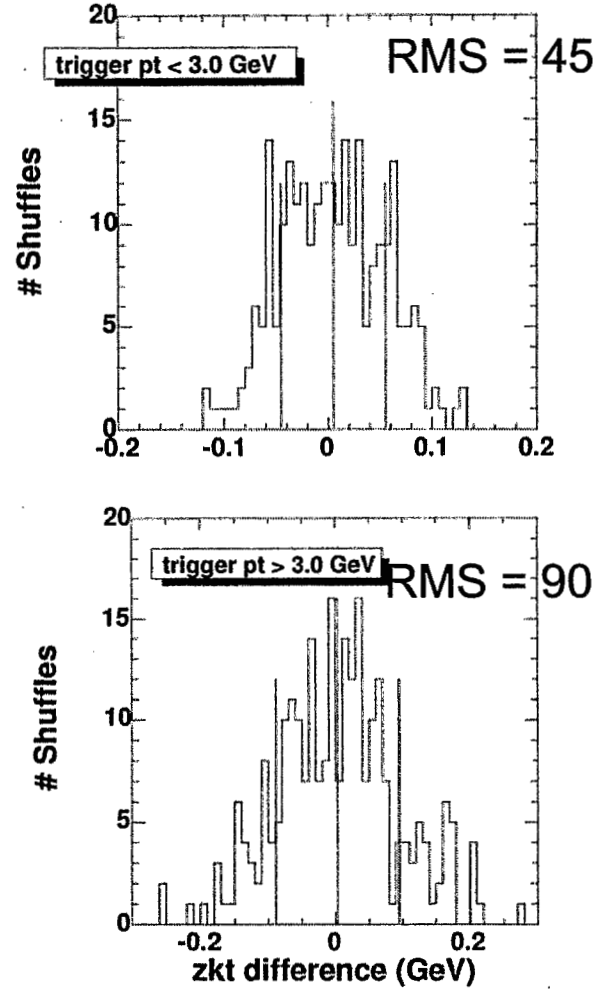
Run03 Data

- We must check the uncertainties to mak sure there are no systematic errors.
  - Bunch shuffling



Systematics Check

- Helicity assignments are randomized, and then the k_T difference calculated for each randomized set.
- The width of the distribution for all the randomized sets should be the same as our statistical errors on the previous plot.



514

Outlook

- Run05 has ~x10 statistics, so that the uncertainty goes from ±75MeV to ±24MeV in the $3.0 < p_{T\dagger} < 5.0$Gev/c bin.
- It has ~x2 in polarization, so the effect grows by ~x4.
- NanoDSTs are produced, analysis should be done in ~2 months.

PHENIX

Summary

- We have an analysis tool that allows us to measure initial state average transverse momentum of jets.
- We are studying this effect in longitudinal spin-sorted collisions to see if there is a spin-dependent coherent transverse momentum.
- Is there a connection to parton OAM? Theoretical guidance needed!
- Run05 is under analysis.

CCJ - Status and Progress

Yasushi Watanabe

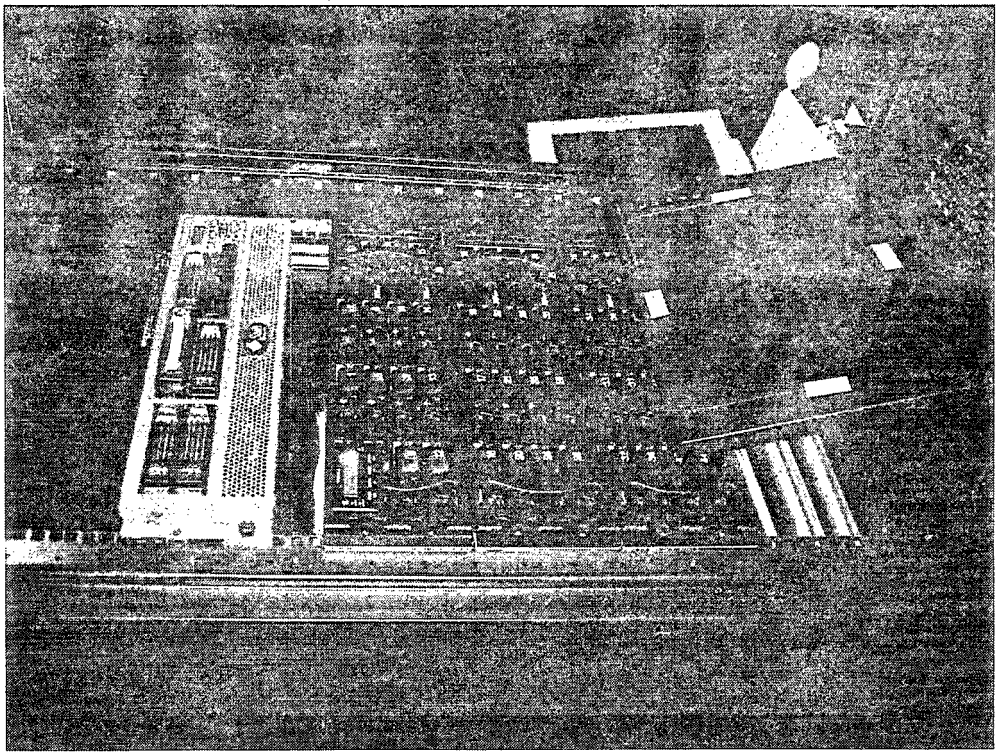
CCJ
- status and progress -

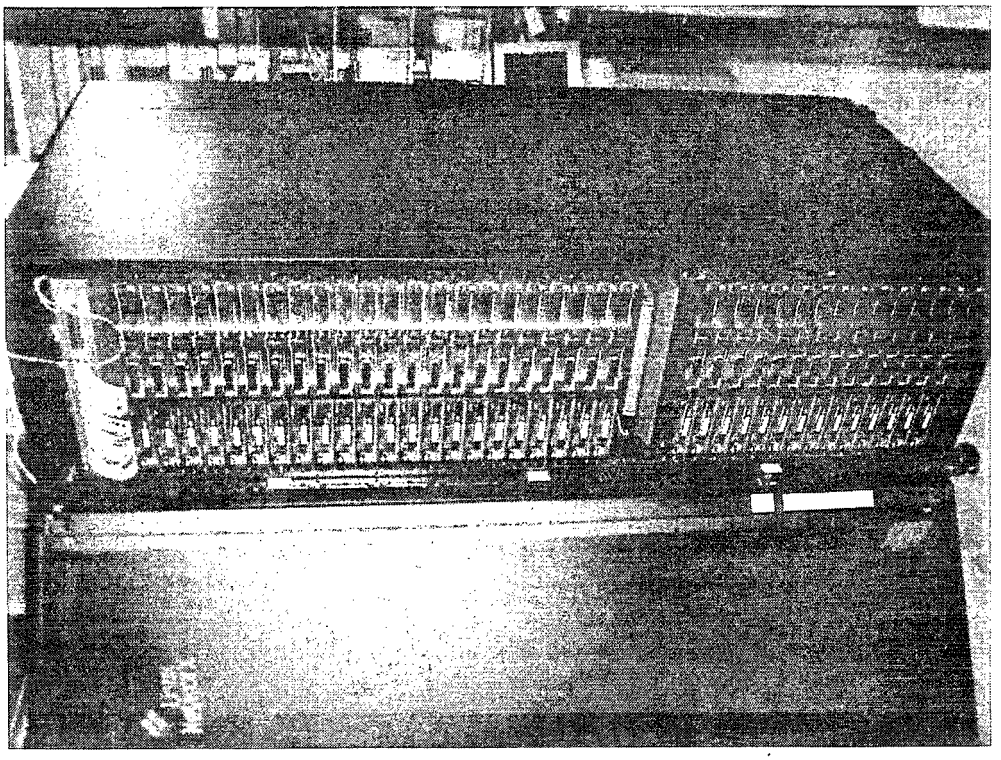
Y. Watanabe
RIKEN/RBRC

Presented on October 10 2005 at RBRC review

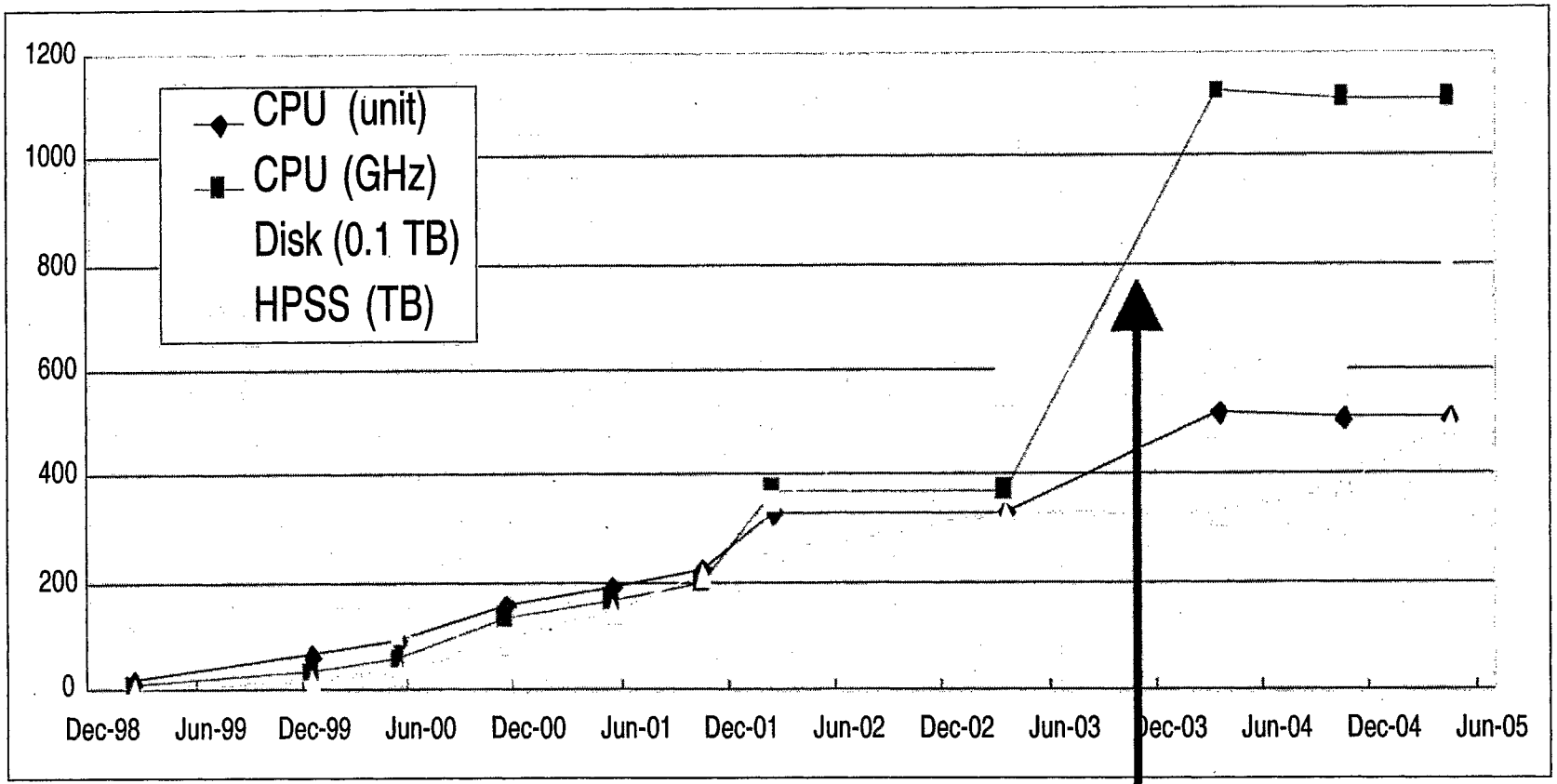
RIKEN CCJ : Overview

- Scope
  - Center for the analysis of **RHIC Spin Physics**
  - Principal **remote** site of computing for **PHENIX reconstruction**
  - **Regional** Asia computing center
- Size
  - CPU performance : 508 Pentium III/4 CPU (Total: 1,111 GHz)
  - Disk Storage : 50 TB
  - Tape Storage: ~800 TB (= 4,000 tapes, expandable to 1.1 PB)
    - Maximum transfer rate: 240 MB/s (30 MB/s/drive x 8 tape drives)



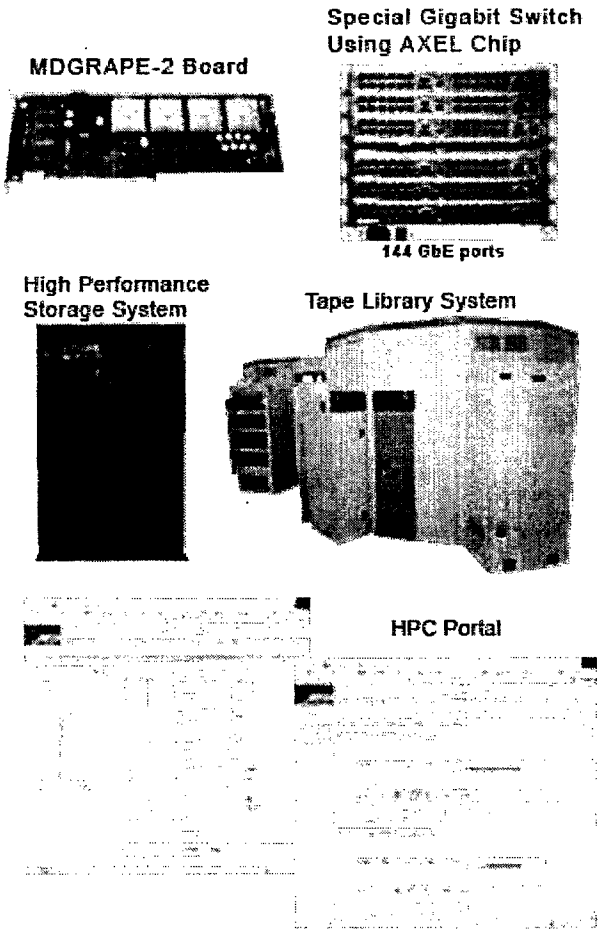


_CCJ growing history



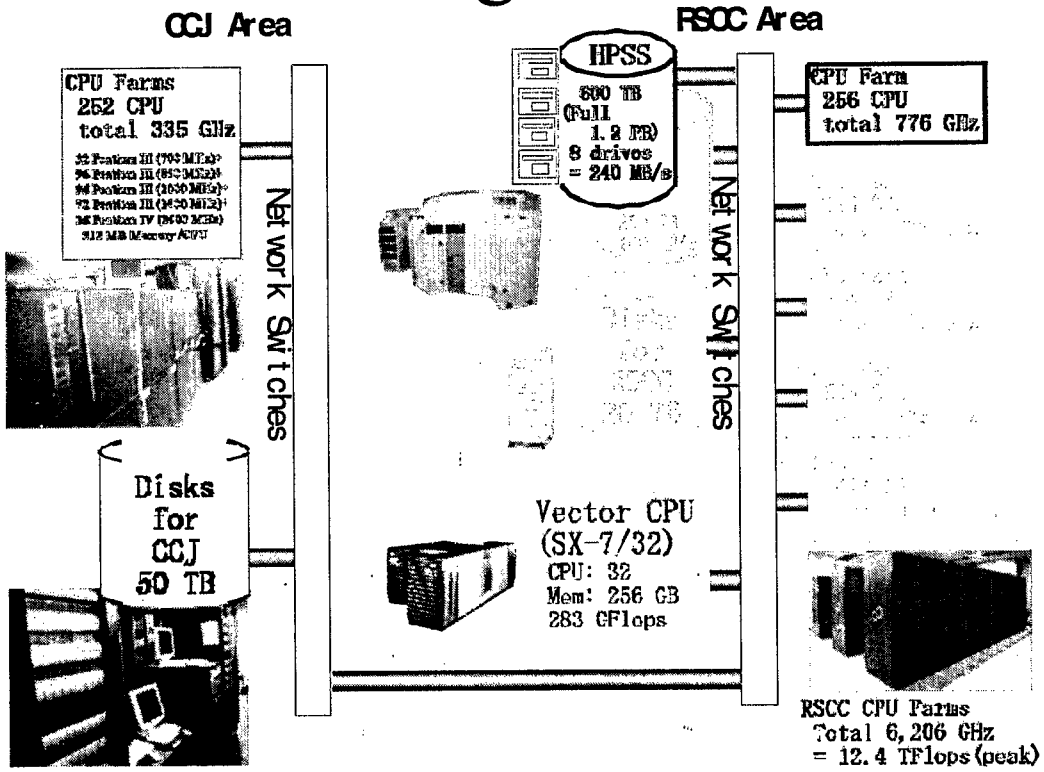
- CPU power reached to Ç times
  - CCJÅ252 CPU Å RSCC pc2c 256 CPU

The RSCC



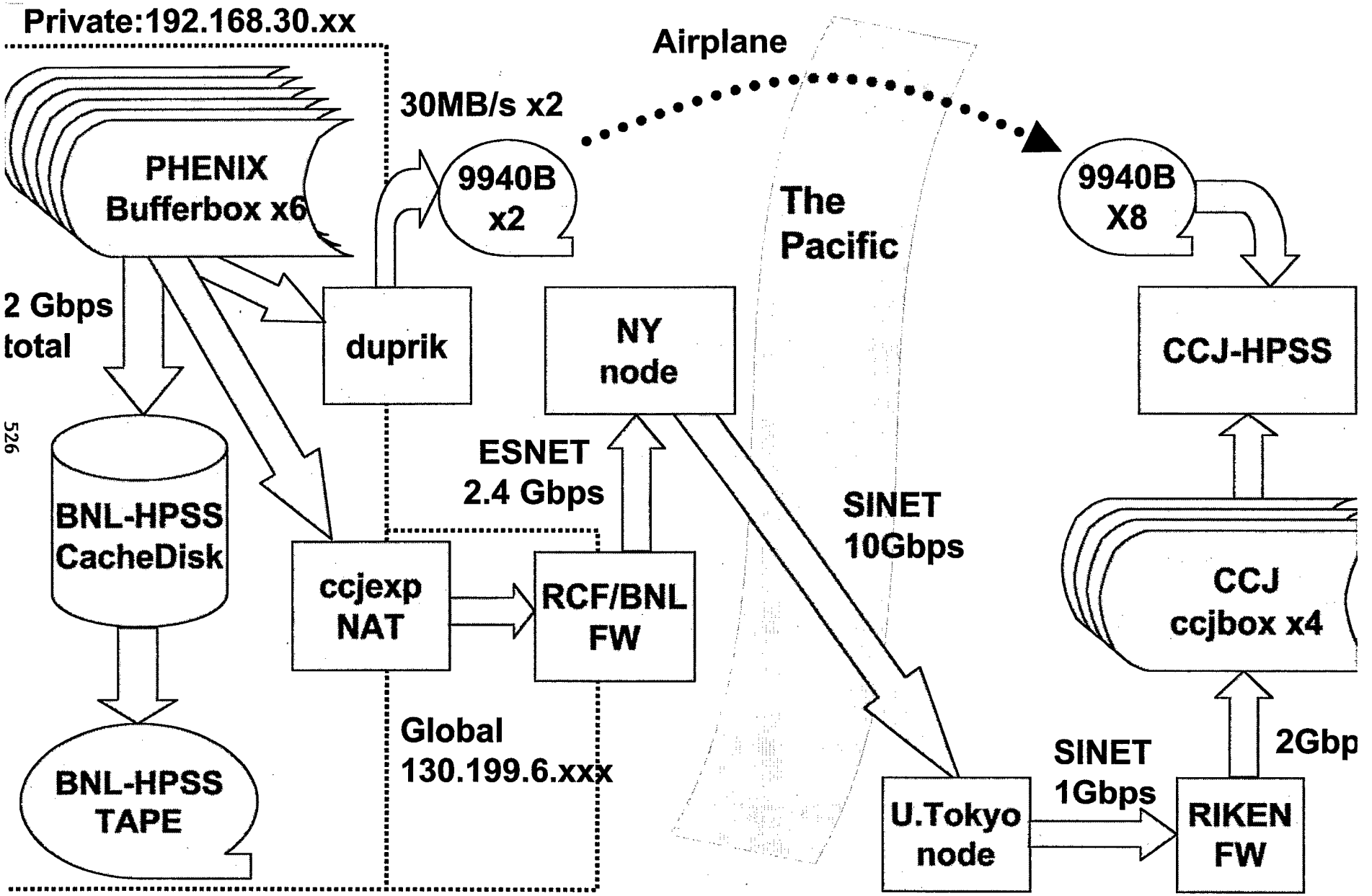
URL: http://accc.riken.jp
Contact us: hpc@riken.jp

Current configuration of CCJ

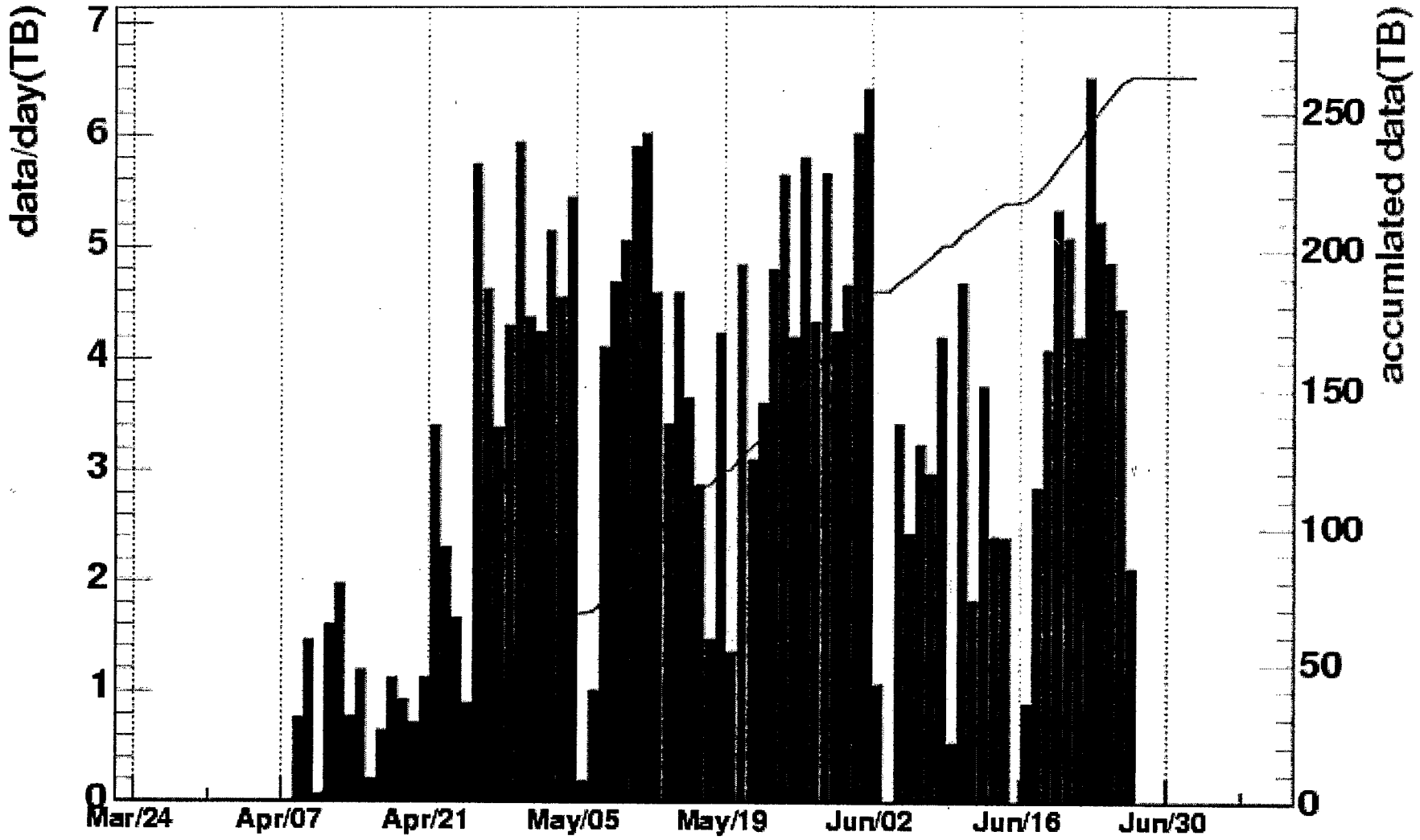


A slide shown in last year

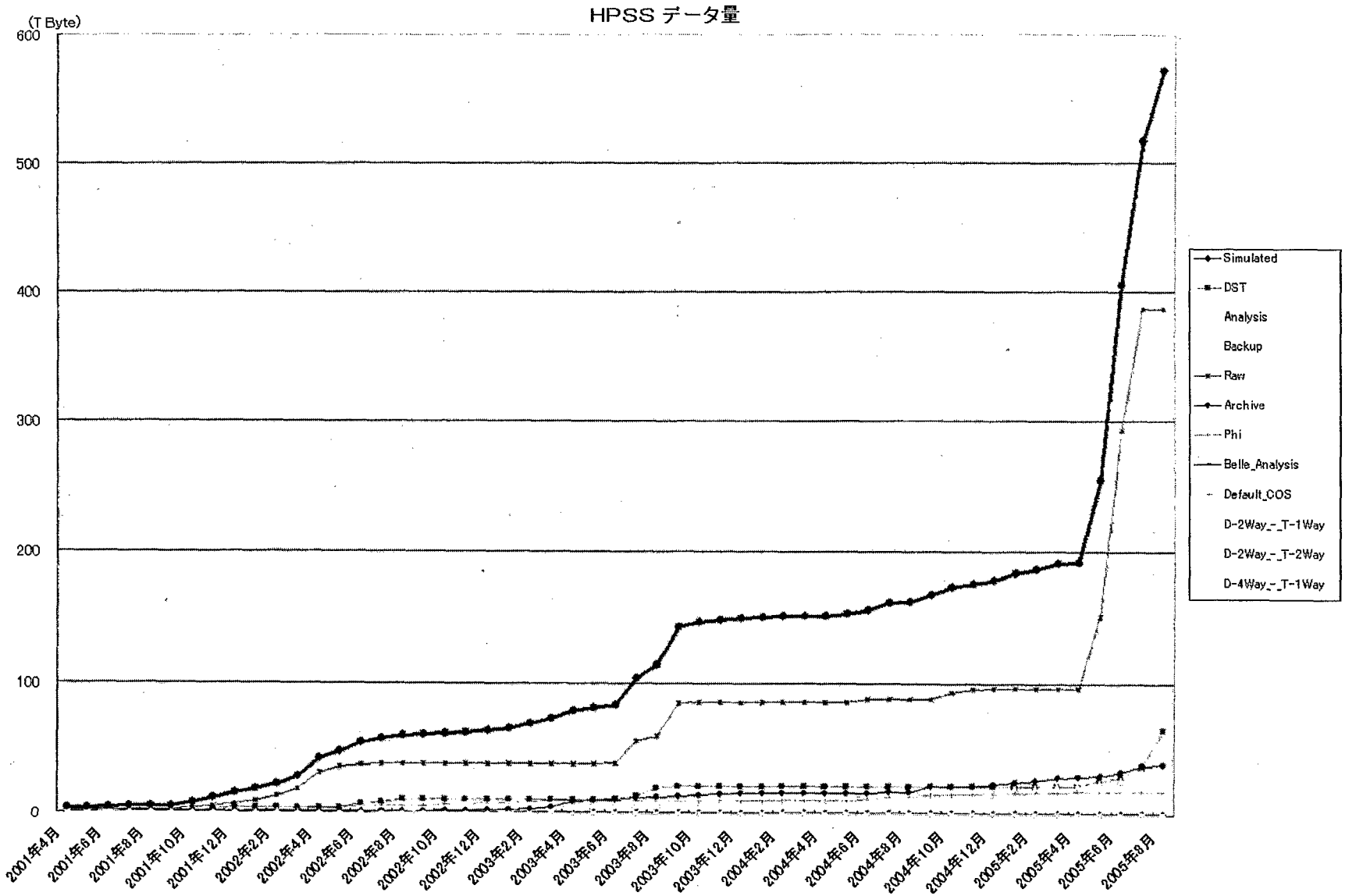
- Going to decide with PHENIX to produce official DST of Run5 pp data at CCJ
  - Because shortage of CPU power at RCF/PHENIX
- Data transfer challenge
  - Estimated pp data volume of Run5: 300~500 TB
    - 60~100 MB/s needs to be sustained for 8 weeks
  - Network transfer: primary option
    - Going to develop
  - Tape transfer: secondary option
    - Already confirmed method


Private:192.168.30.xx
PHENIX
Bufferbox x6
30MB/s x2
9940B
x2
Airplane
The
Pacific
9940B
X8
2 Gbps
total
duprik
NY
node
CCJ-HPSS
BNL-HPSS
CacheDisk
ESNET
2.4 Gbps
SINET
10Gbps
ccjexp
NAT
RCF/BNL
FW
CCJ
ccjbox x4
Global
130.199.6.xxx
2Gbp
SINET
1Gbps
BNL-HPSS
TAPE
U.Tokyo
node
RIKEN
FW

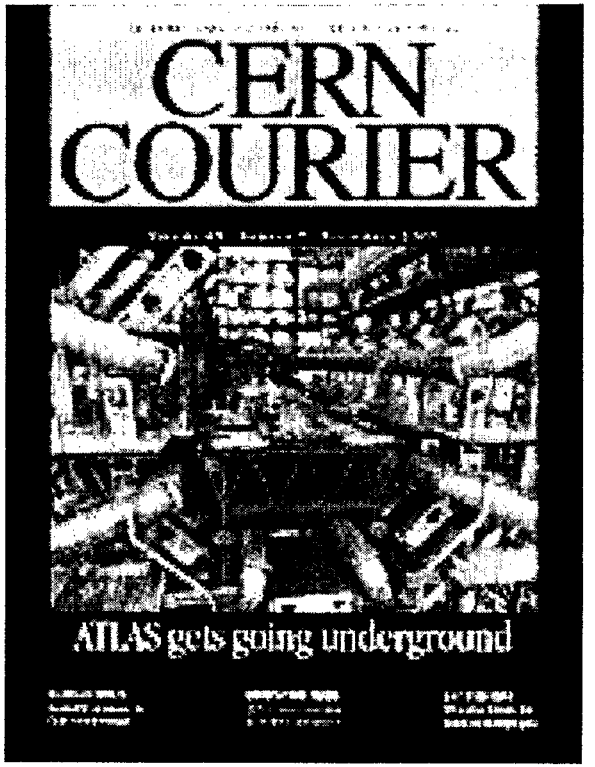
Data transfer challenge



Growth of data stored in the CCJ-HPSS



PHENIX experiment uses Grid to transfer 270 TB of data to Japan



- This seems to be **the first time** that a data transfer of such magnitude was sustained over many weeks **in actual production**
  - http://www.cerncourier.com/main/article/45/7/15

Members of data transfer

- PHENIX
  - M.Chiu, H.Hiejima, M.Purschke, D.Morrison , Shift Crews
- RCF
  - T.Throwe, R.Popescu, S.Misawa, J.Riordan, Y. Dantong
- CCJ
  - T.Ichihara, S.Yokkaichi, A.Kiyomichi, S. Kametani, Y.Watanabe
- …many advisers

Raw data transfer of Run6?

- How much it is?
  - Run5pp ~260 TB: Run6 > 500 TB (= 2,500 tapes)
    - The CCJ-HPSS (silo) will overflow…
  - Three options
    - Introduce newly developed drives (500 GB / cartridge?)
      - Present drive: 200 GB / cartridge
    - Borrow (or invade into) another silo (still empty)
    - Take out cartridges of past run's.
- Network bottleneck
  - 1 Gbps (U. Tokyo – RIKEN) needs to be upgraded
    - Requesting

Analysis for the PHENIX experiment with CCJ in the year

- Official productions and simulations
  - Run5 pp data transfer and production at CCJ
- Major analysis projects
  - Run2-pp vernier scan analysis - Y. Goto
  - Transferring full set of run3 nanoDST to CCJ - M. Kaneta
  - Simulation of Photonic Electron in the PHENIX Run3 d+Au Experiment - F. Kajihara
  - Transfer of nanoDST's from 2nd production for 62.4GeV Au+Au - M. Kaneta
  - PYTHIA-PISA with run3 enviroment - K. Okada
  - run3 200 GeV d+Au nanoDST's copy from RCF to CCJ - M. Kaneta
  - pi0 Simulation of Photonic Electron in the PHENIX Run4 Au+Au Experiment - F. Kajihara
  - Run4 200GeV Au+Au Stripe-2 CNT and PWG nanoDST's copy from RCF to CCJ. - T. Isobe
  - Run4 200GeV Au+Au compact EWG nanoDST's copy from RCF to CCJ - F. Kajihara
  - Study of hadron production at RHIC-PHENIX run4/5 - M. Oka
  - Estimate blocking effect of single electron by materials using PISA for run3pp - M. Togawa
  - Generate run5 pDST for analyzing local pol data - M. Togawa
  - Analysis of Jet Production A_LL - K. Nakano

A Silicon Vertex Tracker for PHENIX

Atsushi Taketani

A Silicon Vertex Tracker for PHENIX

Atsushi Taketani

RIKEN

1. Physics goal
2. Structure of detector
3. Status and plan
4. Expected performance
5. Summary

PHENIX Vertex Group (86 Participants from 15 institutions)

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Brookhaven National Laboratory, Instrumentation Division
J.S. Haggerty, J.T. Mitchell, C.L. Woody, E. O'Brien, D. Lynch
Brookhaven National Laboratory, Physics Department
A.D. Frawley
Florida State University
J. Crandall, J.C. Hill, J.G. Lajoie, C.A. Ogilvie, A. Lebedev, H. Pei, J. Rak, G.Skank,
S. Skutnik, G. Sleege, G.Tuttle
Iowa State University, Ames,
M. Tanaka
KEK
N. Saito, M. Togawa, M. Wagner
Kyoto University
H.W. van Hecke, G.J. Kunde, D.M. Lee, M. J. Leitch, P.L. McGaughey, W.E. Sondheim
Los Alamos National Laboratory
T. Kawasaki, **K. Fujiwara**
Niigata University
T.C. Awes, M. Bobrek, C.L. Britton, W.L. Bryan, K.N. Castleberry, V. Cianciolo, Y.V. Efremenko,
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University of New Mexico
O. Drapier, F. Fleuret, M.Gonin, R. G. de Cassagnac, A. Romana E. Tujuba
Eole Polytechnique
K. Kruita, Y. Inoue
Rikkyo Univesity

RIKEN/RBRC
+supported people

Physics Goals

Open up new horizon!

Heavy Ion program

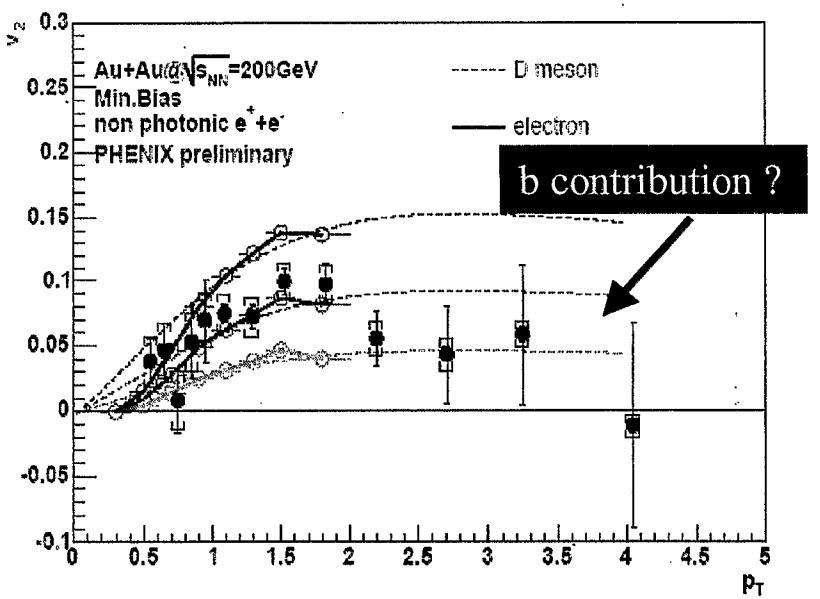
- Potential enhancement of charm production.
- Open beauty production.
- Flavor dependence of jet quenching and QCD energy loss.
- Beauty and charm separation
- Accurate charm reference for quarkonium.
- Thermal dilepton radiation.
- Upsilon spectroscopy, e^+e^- decay channel
- γ -Jet correlation

Spin program

- Investigating nucleon spin structure by polarized proton-proton collider to utilize quark/gluon as probe, instead of DIS lepton.
- gluon polarization by using beauty / charm final state.
- gluon polarization by using γ + jet final state.
- Flavor decomposition by using W->e channel.

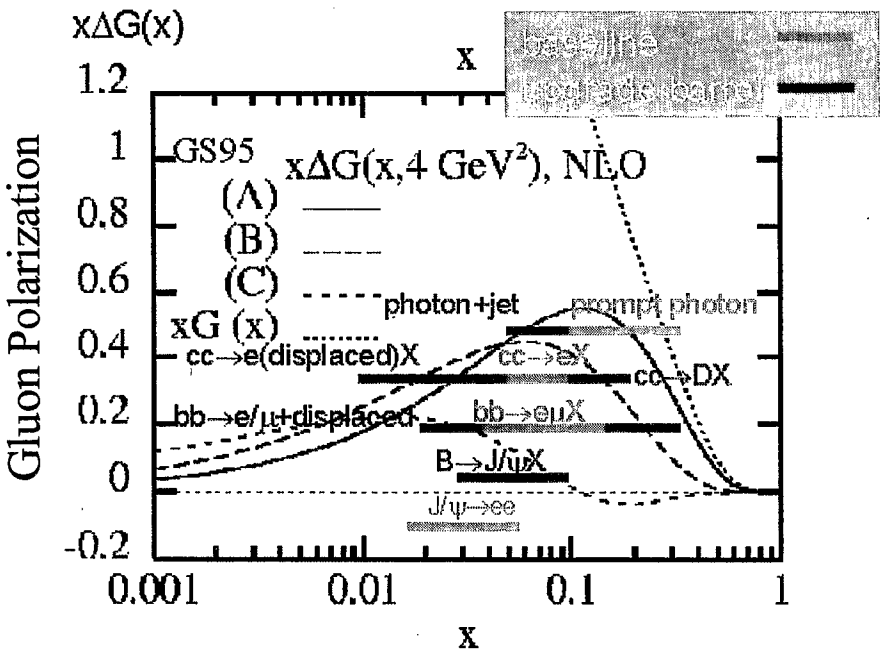
Physics Goal

Heavy Ion Program



Pt [GeV]

Spin Program



- **Charm and bottom identification by displaced vertex**
- **Jet identification with larger acceptance**

NSAC recommendation

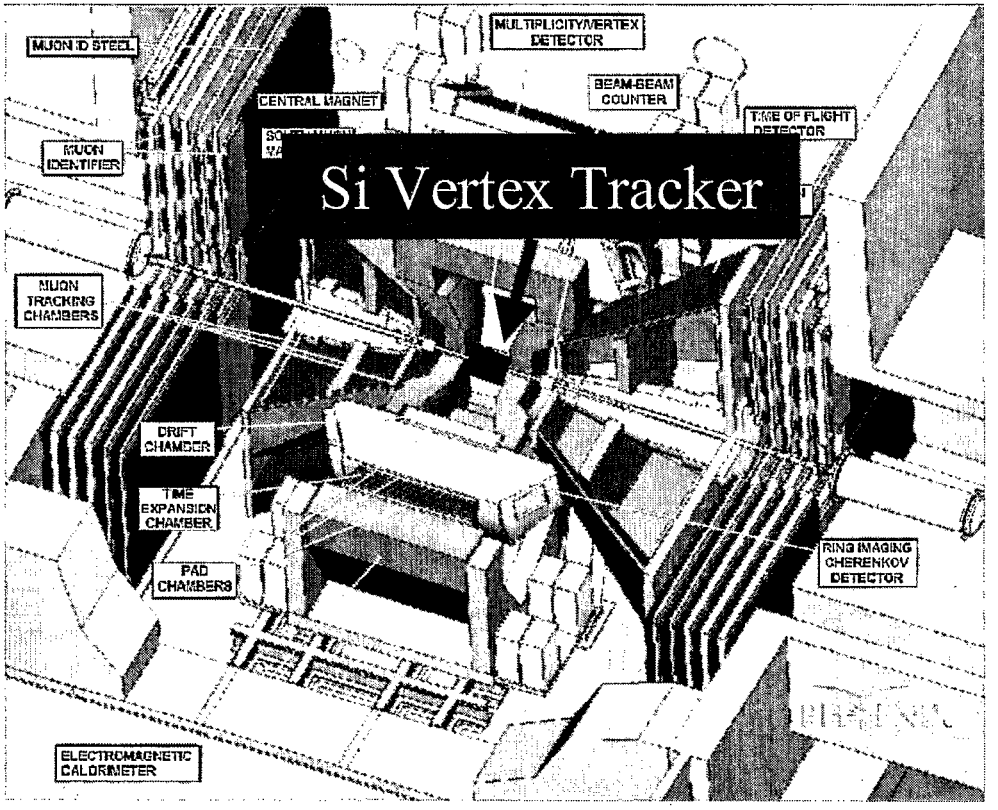
October 7, 2004

Within a constant level of effort budget, the Subcommittee recommends that certain essential investments be made. These include:

- **Construction of the PHENIX Silicon Vertex Tracker** and the STAR Time-of-Flight Barrel;
- Participation in the LHC Heavy-Ion program;
- Investment in RHIC accelerator and detector R&D;
- Construction of the EBIS;
- Support at the present level for university and national laboratory research;
- Provision for RHIC running time sufficient to preserve the integrity of the Heavy-Ion and Spin Physics programs.

Current PHENIX

Pioneering High Energy Nuclear Interaction eXperiment



PHENIX Detector

1 Central Arm

e, g, Charged Hadrons detection
|h|<0.35, Df=p

2, Muon Arm

m detection
1.2<|h|<2.4, 2p in f

3, Forward detectors

Luminosity Monitoring
Centrality
Local polarimetery

✓Good particle identification **(But no direct b/c identification)**

✓High Rate and High Detector granularity.

✓Limited geometrical coverage **(Not 2π in central region)**

Requirements for Vertex Tracker

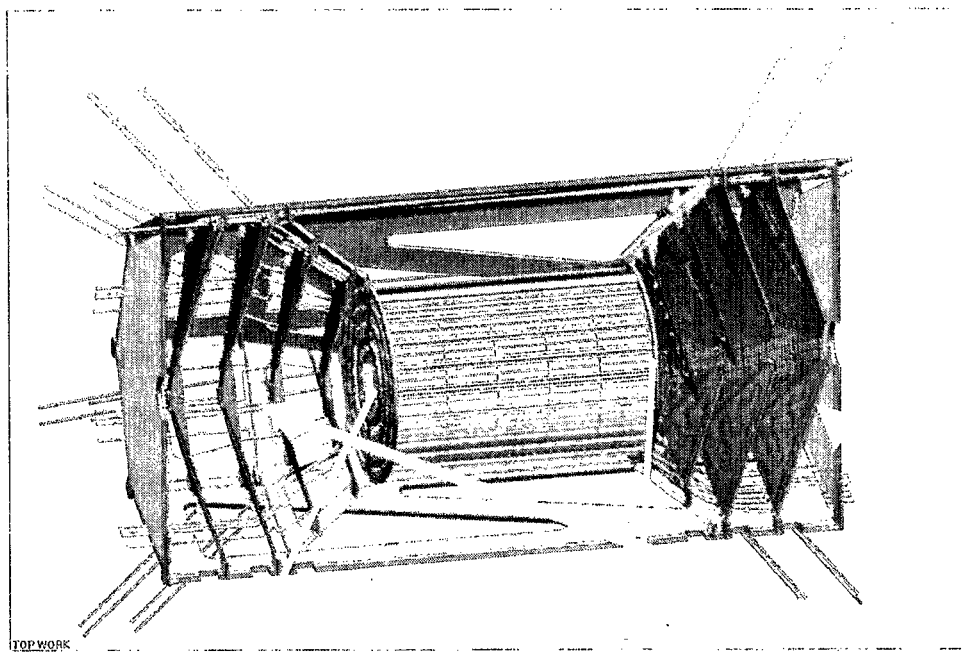
Physics side

- High precision tracking for displaced vertex measurement. 40μm displaced vertex resolution, cτ ~ 100μm(D), ~400μm(B)
- Large coverage tracking capability with momentum resolution (|η|<1.2 , and full azimuthally with σ/P ~ 5%P)

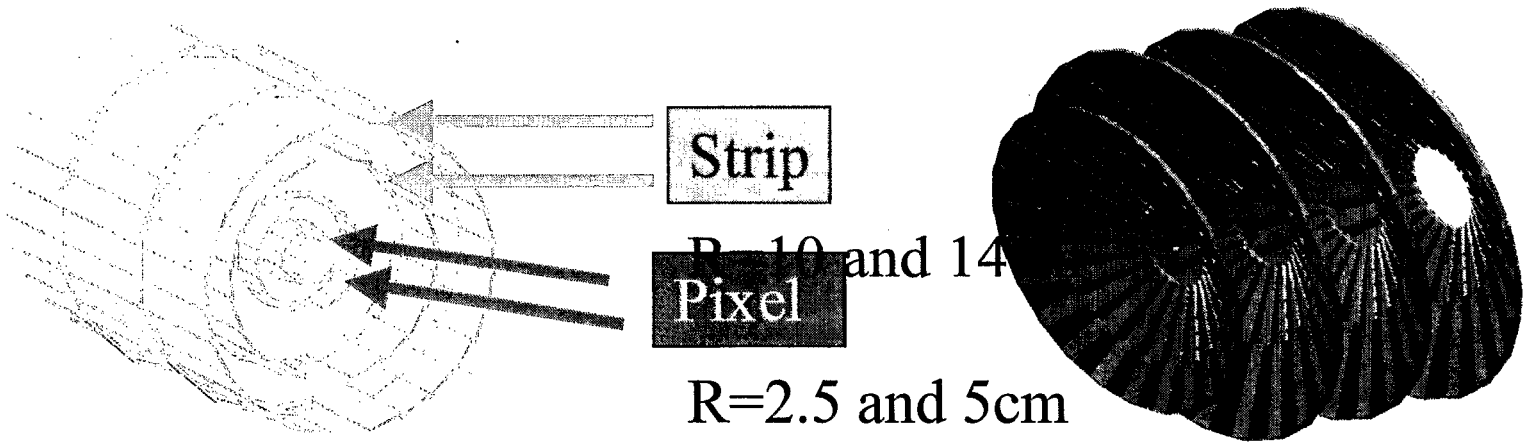
[redacted]

- High charged particle density 'dN/dη' ~ 700 @η=0
- High Radiation Dose ~100KRad@10Years
- High Luminosity $2\times10^{32} cm^{-2}s^{-1}$ @PP -> High rate readout
- Low Material Budget <- avoid multiple scattering and photon conversion for electron measurement by outer detectors.

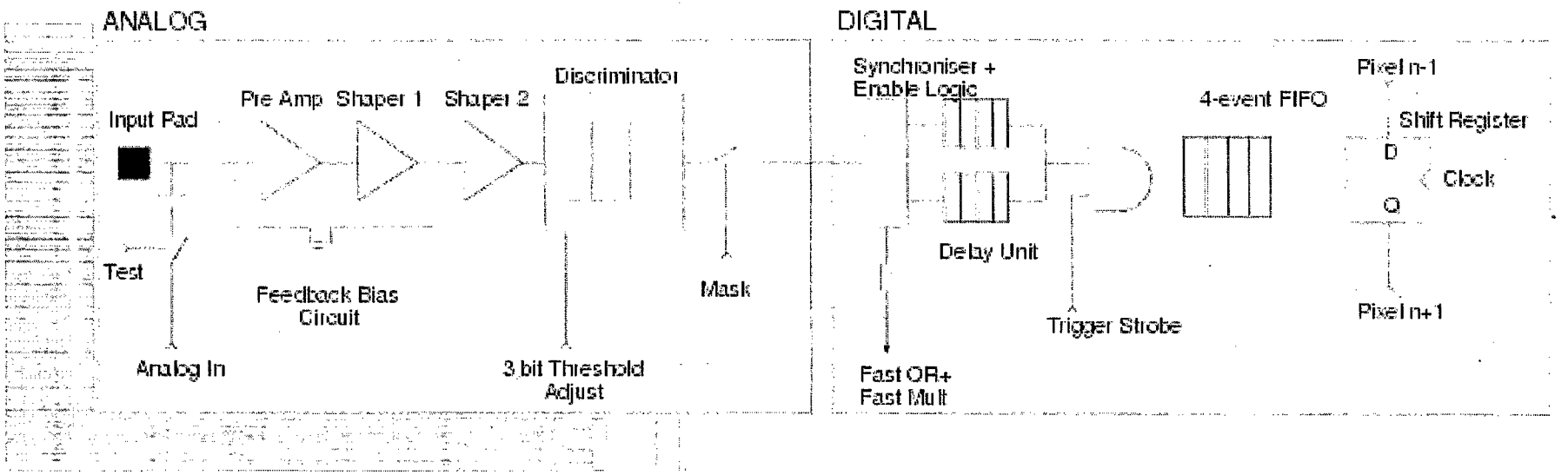
Structure



- Barrel region
  - $|\eta|<1.2$, almost 2π in ϕ
  - Pixel sensor at inner 2 layers
  - Strip sensors at outer 2 layers
- Forward region
  - $1.2<|\eta|<2.7$, 2p in ϕ
  - 4 layers of mini strip (50 x 2000 to 11000 μm)
  - Trigger capable



PIXEL (Sensor and Readout)



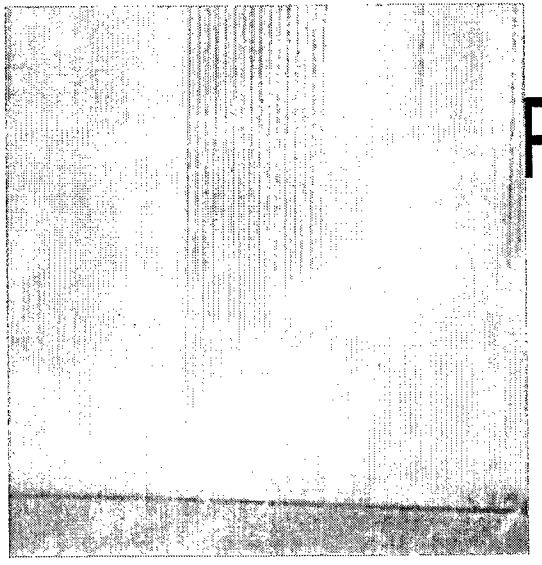
Pixel size(Φ x z) 50 μm x 425 μm
Sensor Thickness 200um
$\Delta r\Phi$ = 1.36cm, Δz = 1.28 cm
256 x 32 = 8192 channel / sensor
4 sensor / chip
4 chip / ladder

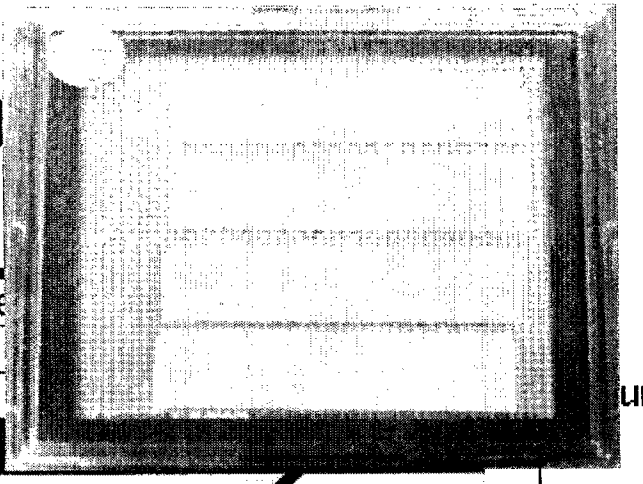
Readout by ALICE_LHCB1 chip

- Amp + Discriminator / channel
- Bump bonded(2 dim. Soldering) to each pixel
- Running 10MHz clock (RHIC 106nsec)
- Digital buffer for each channel > 4usec depth
- Trigger capability > FAST OR logic for each crossing

Used at NA60 (Rad hard)

PIXEL reado





Al-Kapton Bus readout to minimize material (120micron pitch)

Ground

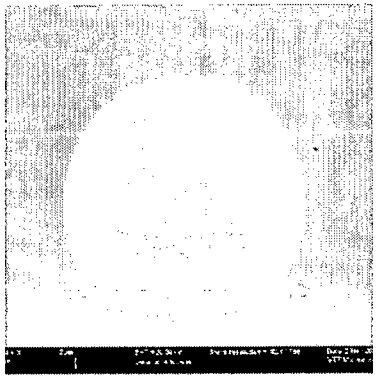
Silicon Pixel Sensor

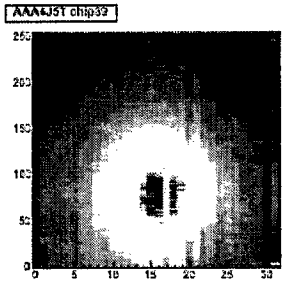
200um

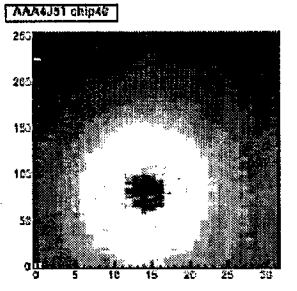
Bump bonding

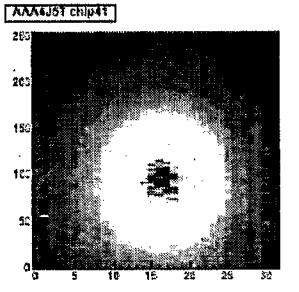
Read out chip

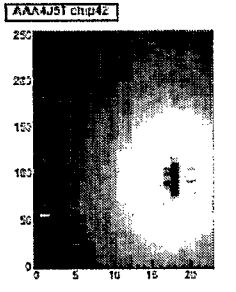
400um



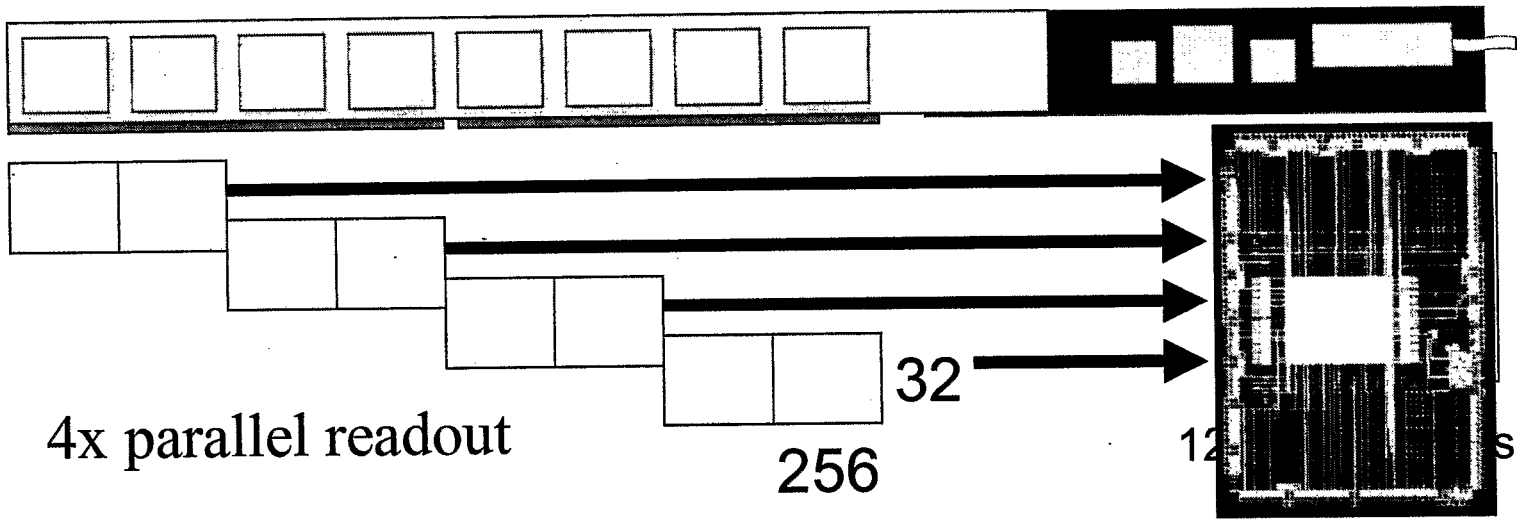








PIXEL readout



✓Ver.1 is running.

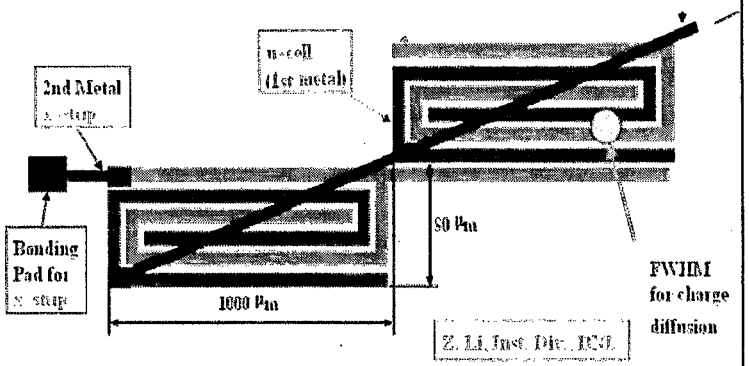
✓Ver.2 will came in Summer

PHENIX Digital Pilot

LICE chip is 32bit input/40MHz x 16bit output

Strip layer

Sensor elements:



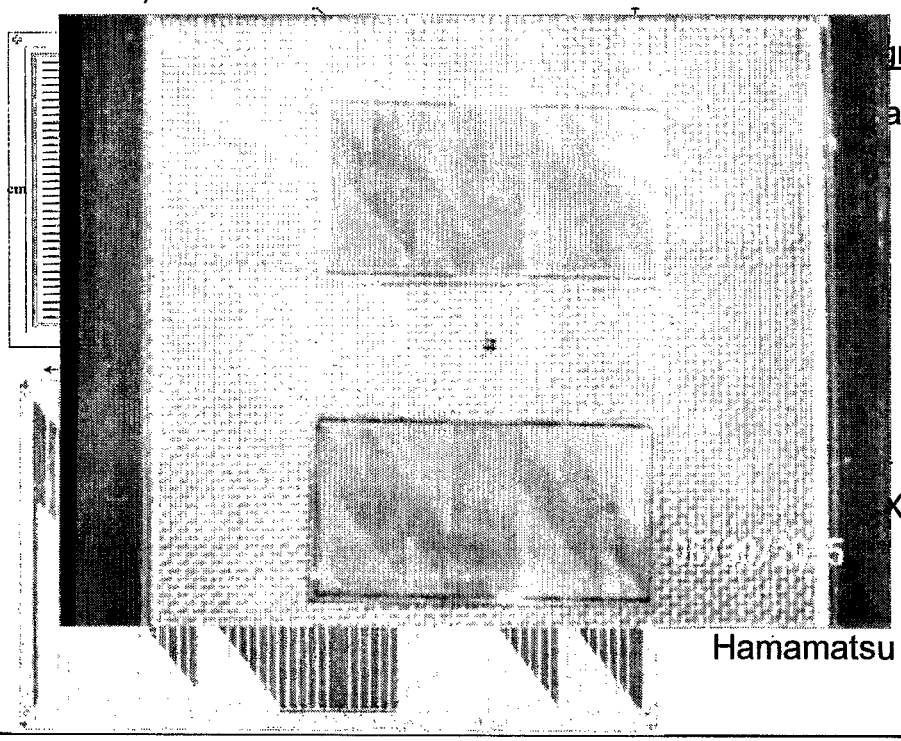
Pixels: 80 μm × 1 mm, projective readout via double metal XU/V "strips" of ~3 cm length.

Developed at BNL Instrumentation Gr.

✓**Single sided**

✓**1+1 dimensional readout (X and U direction)**

Two strip-pixel arrays on a single-sided wafer of 500 μm thickness, with 384 + 384 channels on 3 x 3 cm^2 area.



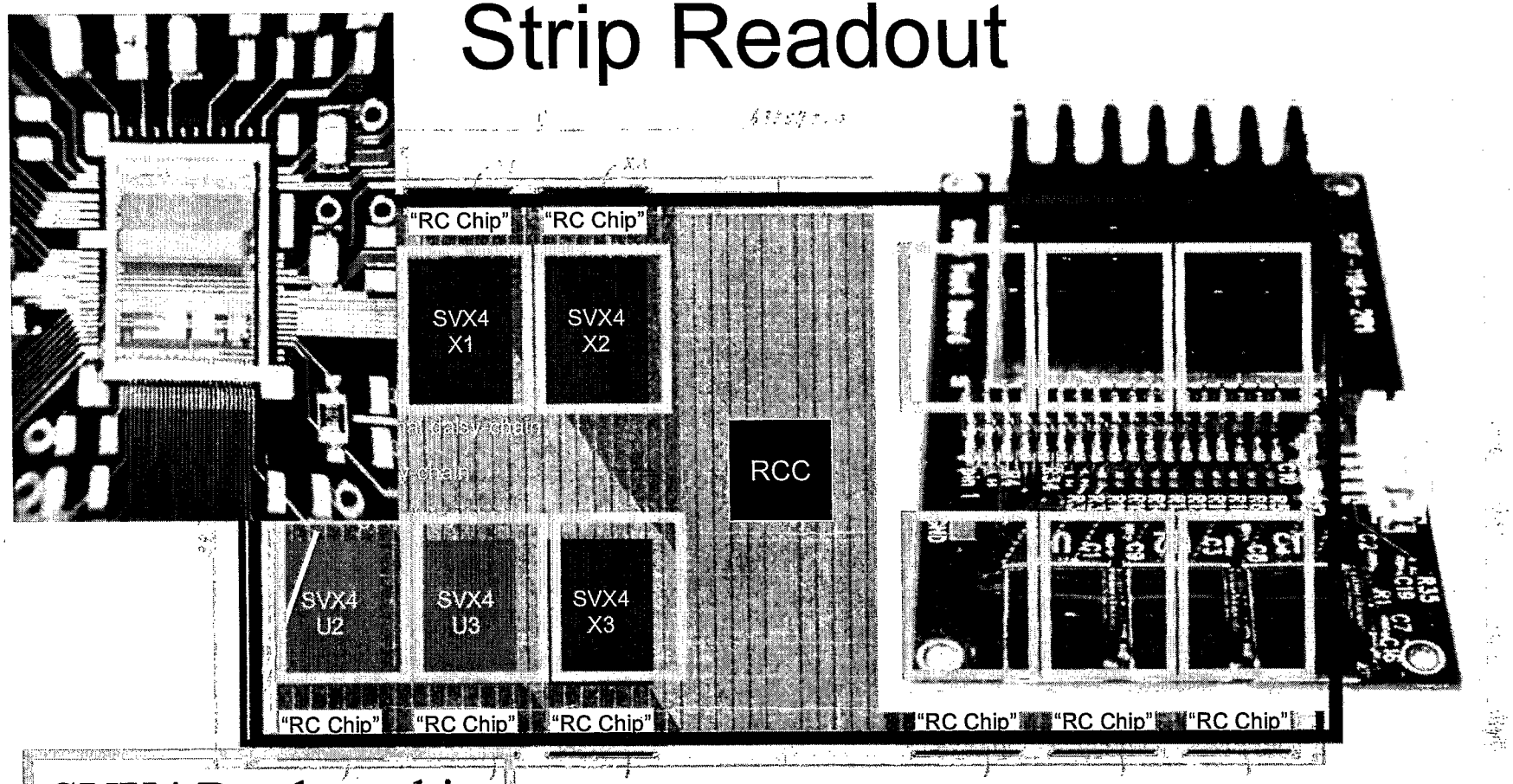
Hamamatsu

✓**3cmξ3cm sensor ξ2 / chip**

✓**768 X strip and 768 U strips/chip**

Position resolution is 25μm by test beam

Strip Readout



SVX4 Readout chip

- **Developed by FNAL for TEVATRON RUN2b (Rad hard)**
- **8 bit ADC for each channel**
- **128 channel per chip**

Readout Testboard (Testing now)

5cm-5cm sensor

- ✓ **3 SVX Chip**
- ✓ **Packing factor is same**
- ✓ **Control by onboard FPGA**

Schedule and status

• Pixel Readout test	End of 2005
• Strip Readout test	Fall of 2005.
• Structure design study	Start now
• Prototype ladder	Early 2006
• Production (Japan)	Start in 2005
• Production (US)	2007
• Installation complete	2009

(Possible early partial implementation)

- Total cost ~8M US$ (Japan, US, France)

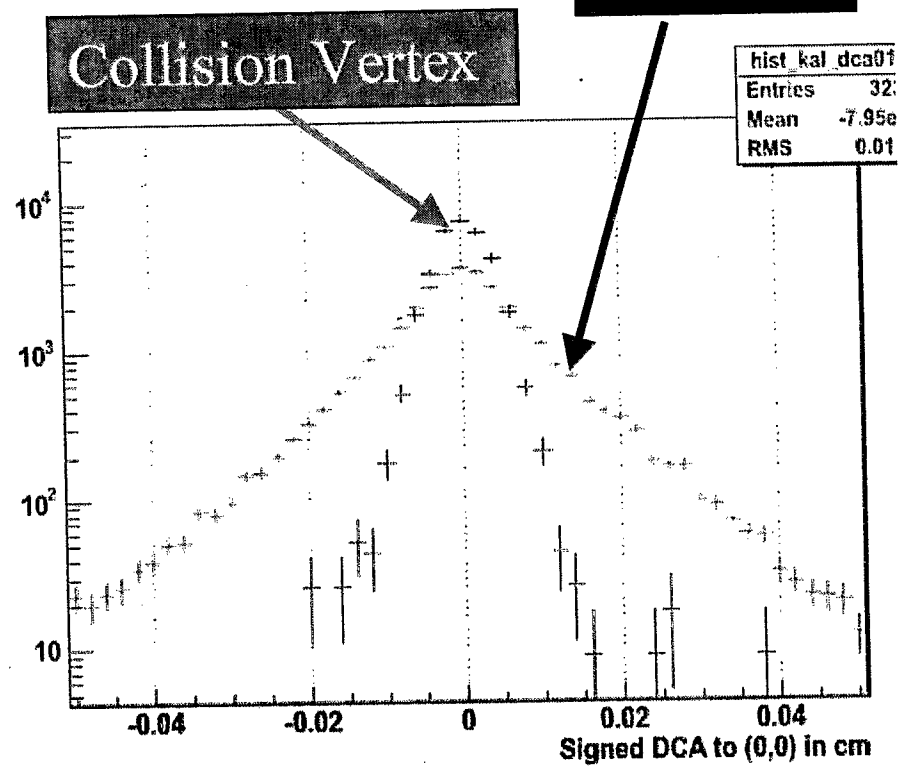
Expected Performance

Layer	radius	Sensor	Occupancy	
Layer 1	2.5 cm	Pixel	**0.53 %**	
Layer 2	5.0 cm	Pixel	**0.16%**	
Layer 3	10.0 cm	Strip	**4.5 %** (x-strip)	**4.7 %** (u-strip)
Layer 4	14.0 cm	Strip	**2.5 %** (x-strip)	**2.7 %** (u-strip)

Expected occupancy at Au-Au 200GeV most central event

Chi2 < 1.0

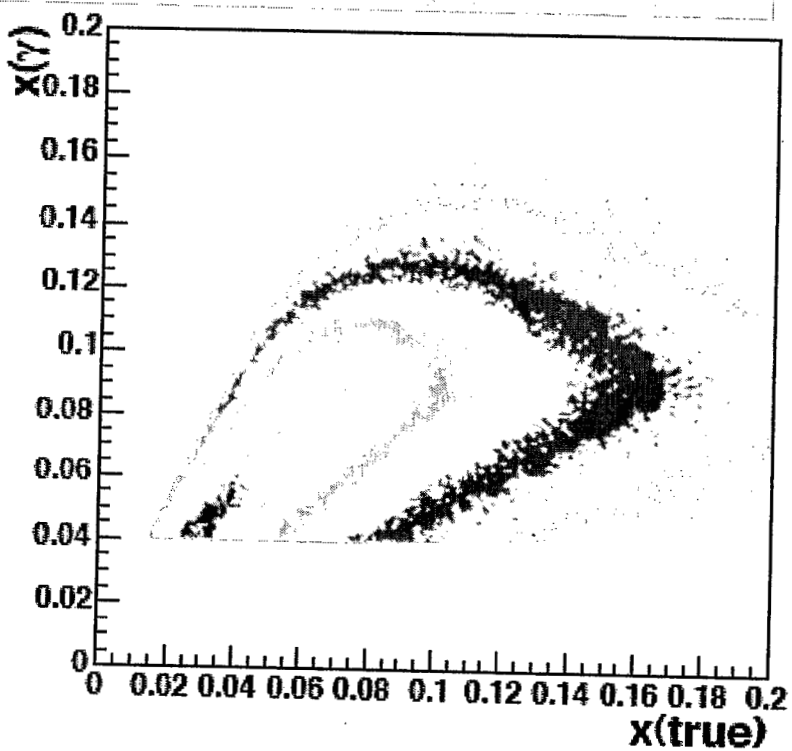
[redacted]



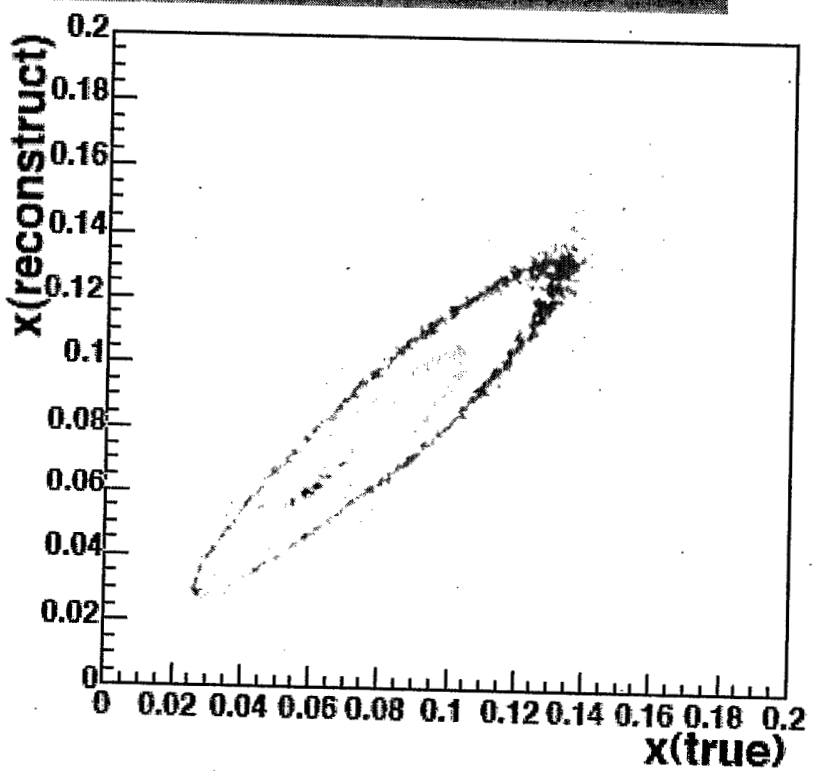
Distance to the Closest Approach [cm]

Spin performance
parton X reconstruction by γ + Jet

Using only Photon information



Photon + 2π VTX tracker



Great improvement with VTX

Summary

- PHENIX Silicon Vertex Tracker will open new physics horizon for both Heavy Ion and Spin program of RHIC.
- There are two of inner pixel layers, two of outer strip layers and forward mini-strips
- Hardware R&D work is on going.
- Completer installation in 2009 for RHIC RUN9(2009/2010).
- Plans underway for early partial implementation.

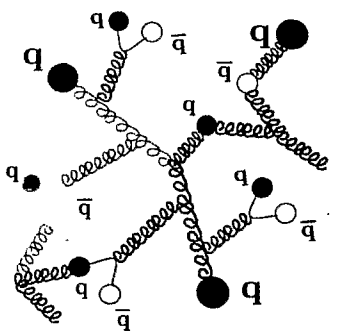
PHENIX Muon Trigger Upgrade

Wie Xie

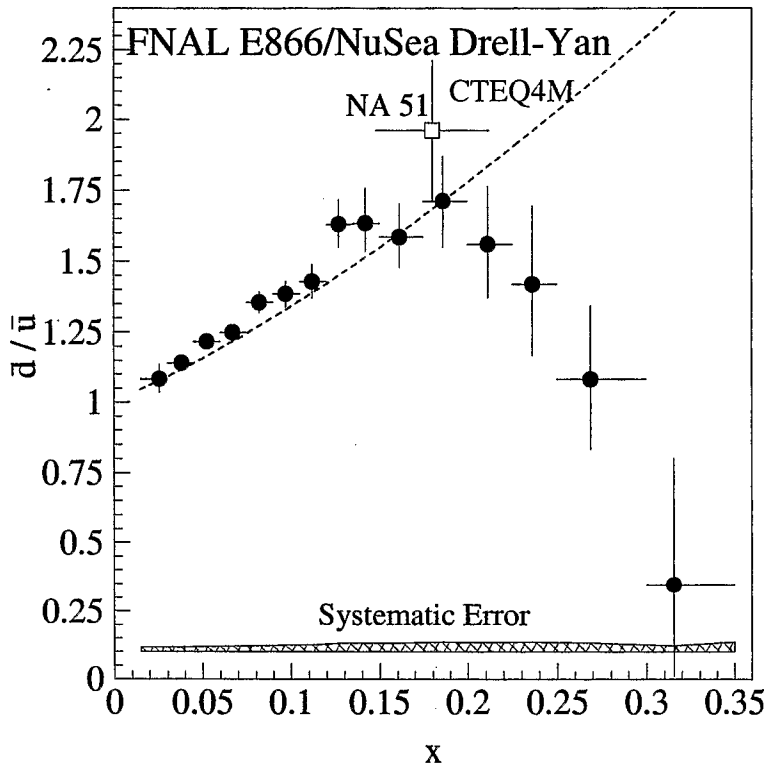
PHENIX Muon Trigger Upgrade

W. Xie (RBRC)

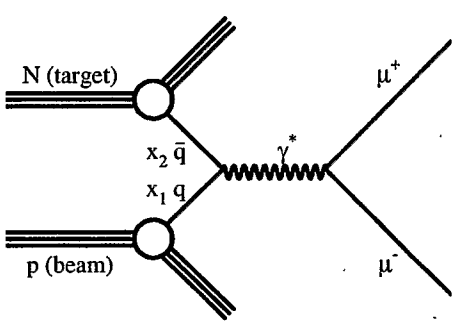
PHYSICS Motivation: *Spin Dependent Quark and Anti-Quark Distributions*



$$\bar{u}(x) \approx \bar{d}(x) \ ??$$



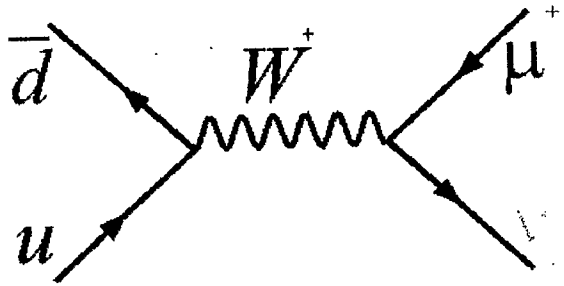
Drell-Yan Process:



$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}[1+\frac{\bar{d}(x)}{\bar{u}(x)}]$$

PHYSICS Motivation: *Spin Dependent Quark and Anti-Quark Distributions*

Question: $\Delta\bar{u}(x_1) = \Delta\bar{d}(x_2)$??



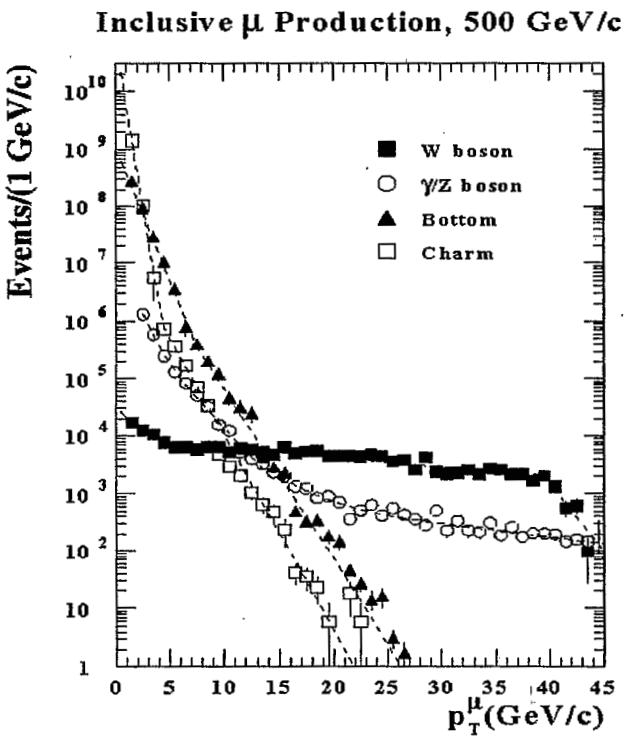
$$A_L(W^+) = \frac{\Delta u(x_a)}{u(x_a)} \quad , X_a >> X_b$$

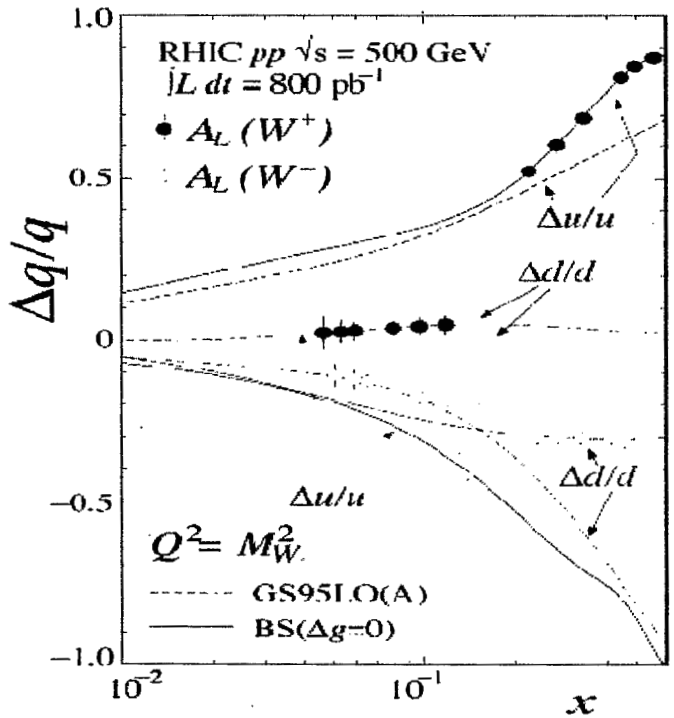
$$A_L(W^+) = -\frac{\Delta\bar{d}(x_b)}{\bar{d}(x_b)} \quad , X_b >> X_a$$

Direct measurement of quark/antiquark spin:

$$A_L^W = \frac{1}{p} \times \frac{N_-(W) - N_+(W)}{N_-(W) + N_+(W)} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

PHYSICS Motivation: *Spin Dependent Quark and Anti-Quark Distributions*



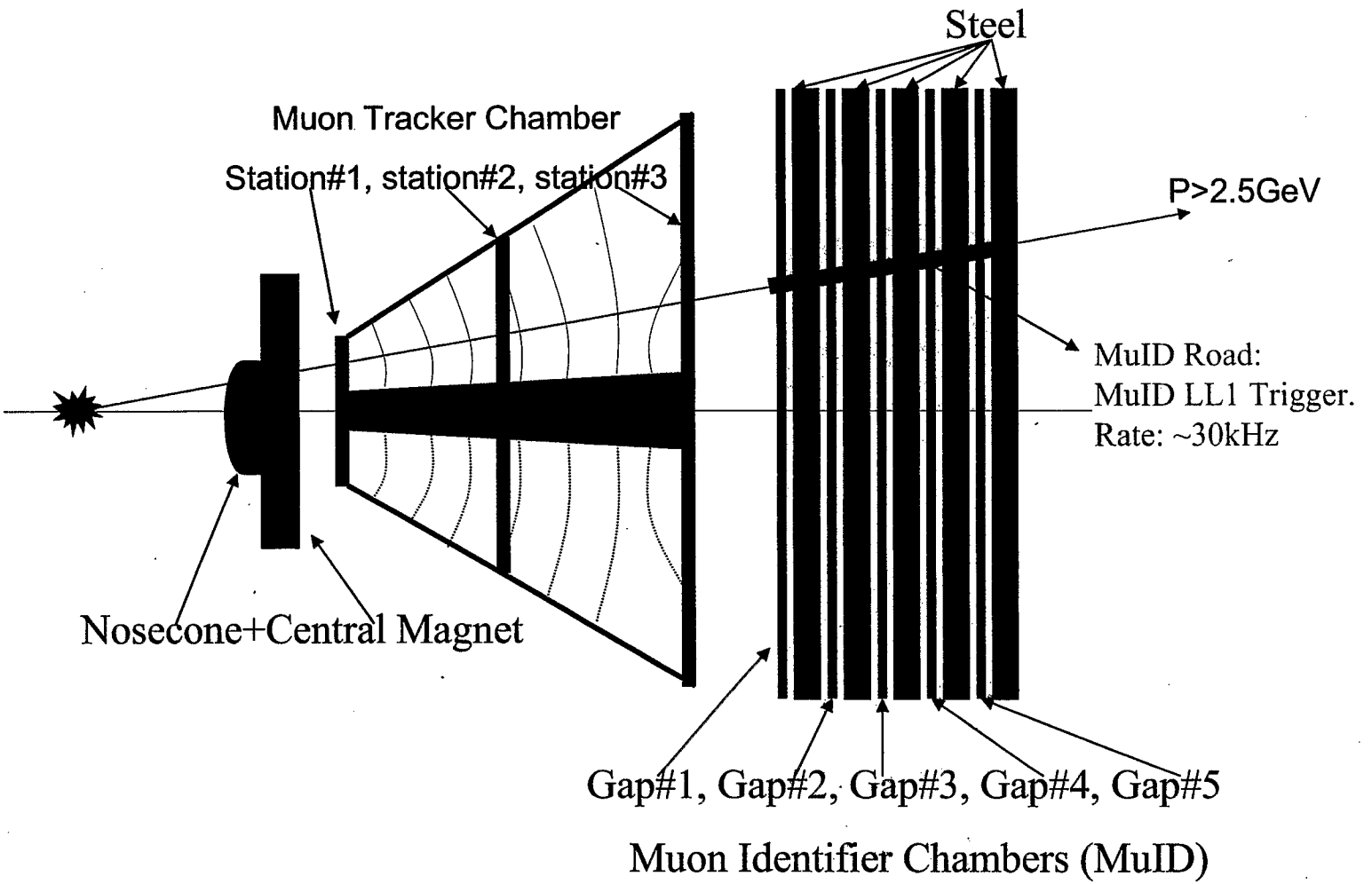


Accurate Measurement of Quark/Antiquark spin

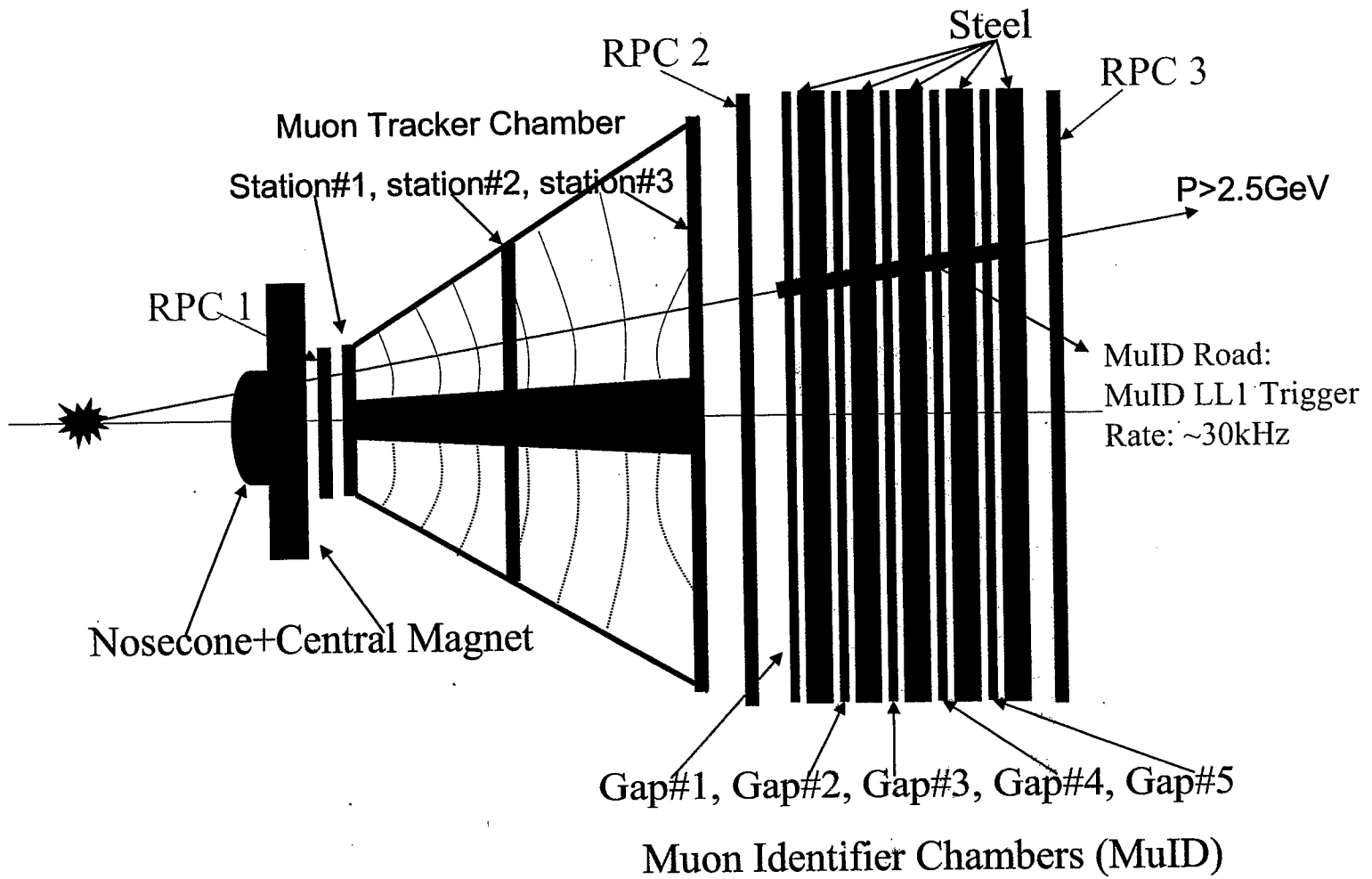
Major Problem to be Solved first: Muon Trigger Upgrade

- collision rates in 500GeV run: ~12MHz,.
- PHENIX DAQ bandwidth: 5KHz (can go up to 12kHz)
- Bandwidth assignment for muon trigger: 1kHz.
- Need trigger rejection factor $= \frac{\text{Collision Rate}}{\text{Trigger Rate}} = \frac{12MHz}{1kHz} \approx 10^4$
- Current muon level-1 trigger rate: ~30kHz.
- **need additional rejection of 30**

PHENIX Muon Arms



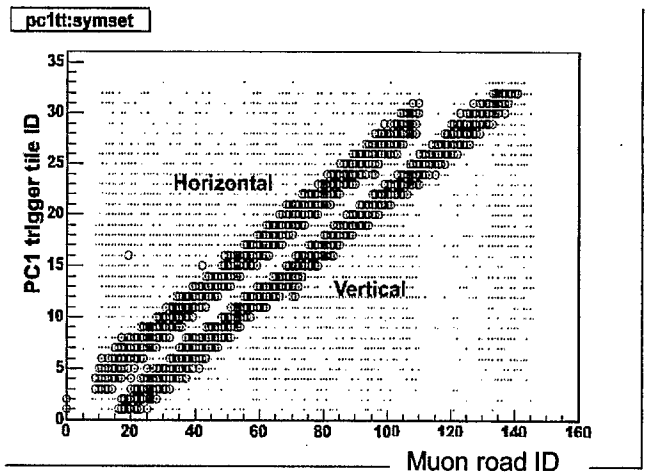
Muon Trigger Upgrade Plan

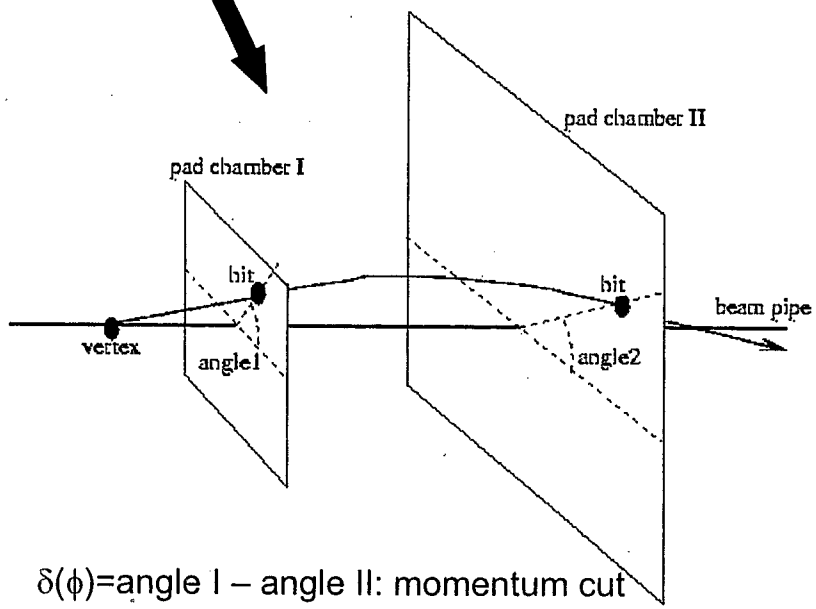


Muon Trigger Upgrade Plan

MuID Road match RPC hits X momentum cut from RPC = Trigger Upgrade

(Look up Table)





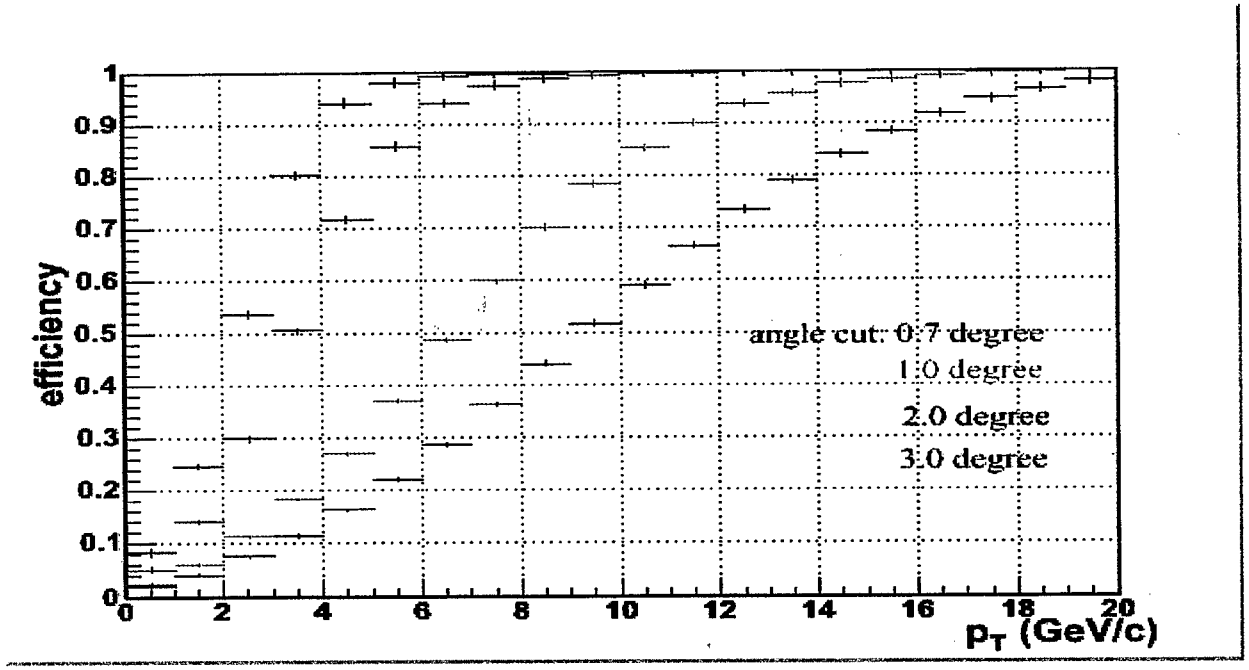
$\delta(\phi)$=angle I – angle II: momentum cut

$\delta(\phi)$ deg	<0.7	<1.0	<2.0
Pt (GeV)	10.0	7.0	3.5
rejection	36000	19980	10090

Enough rejection power achieved

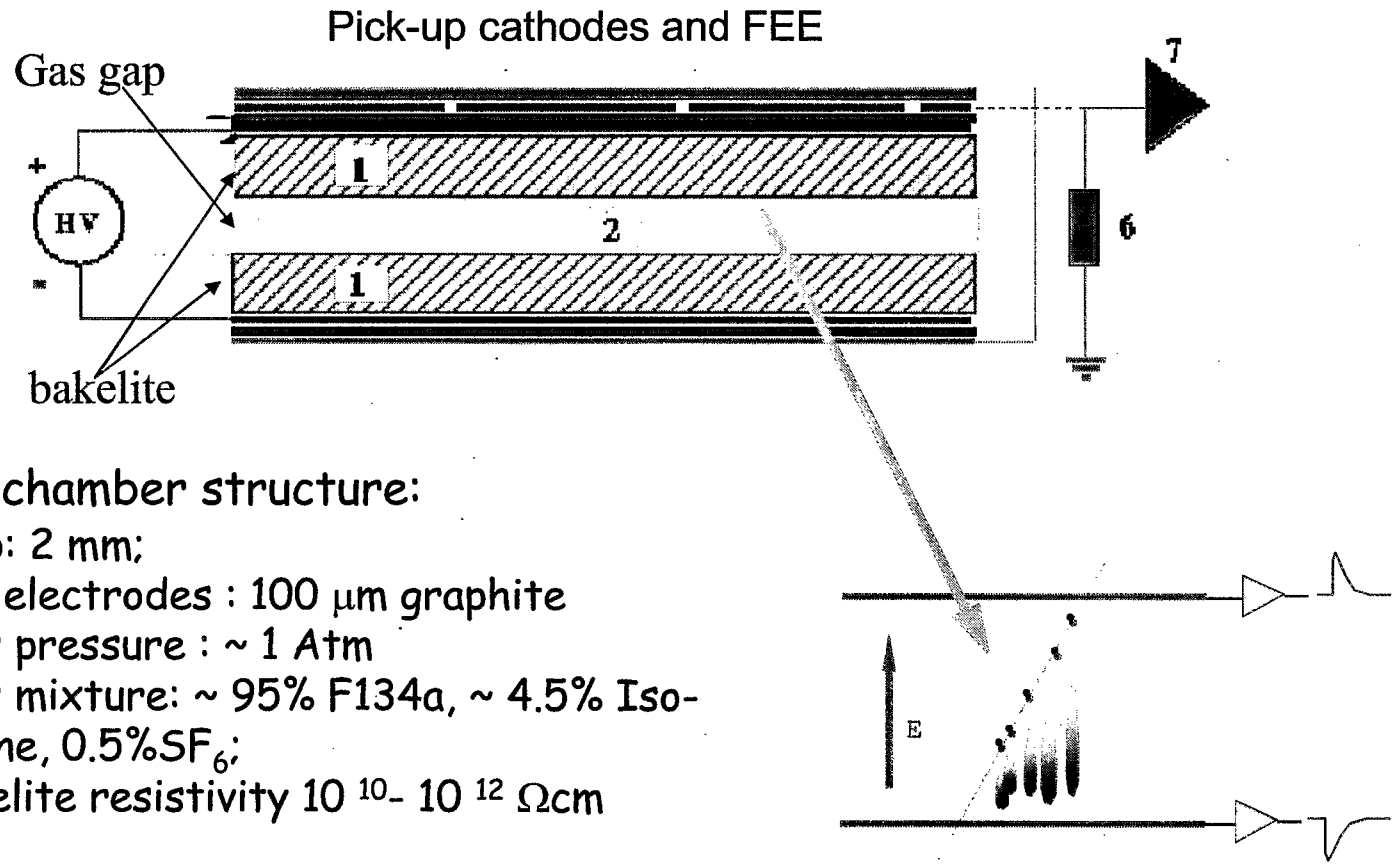
Muon Trigger Upgrade Plan

$$\text{efficiency} = \frac{\text{accepted signal}}{\text{total input signal}}$$



Very Efficient for High pT Muons

Trigger Chamber Technology: Resistive Plate Chamber



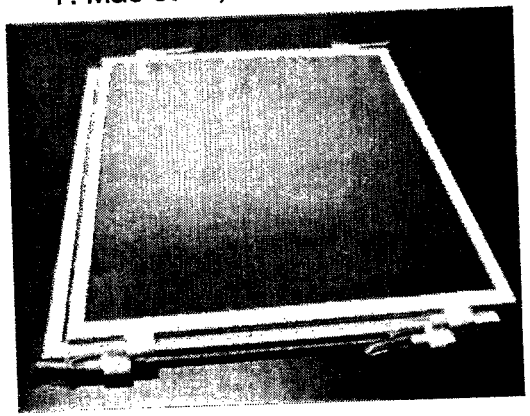
The chamber structure:

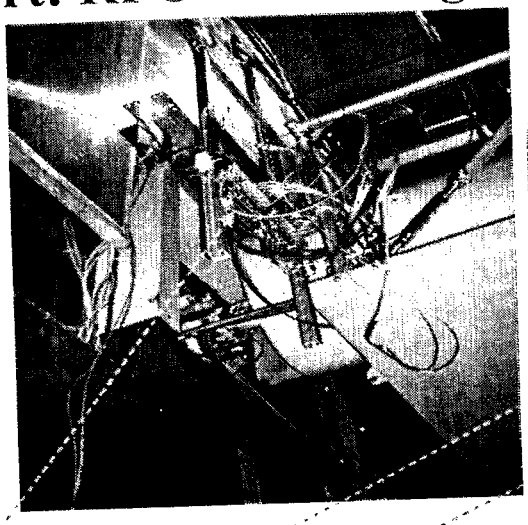
- Gap: 2 mm;
- HV electrodes : 100 μm graphite
- Gas pressure : ~ 1 Atm
- Gas mixture: ~ 95% F134a, ~ 4.5% Iso-Butane, 0.5%SF_6;
- bakelite resistivity 10^{10}- 10^{12} Ωcm

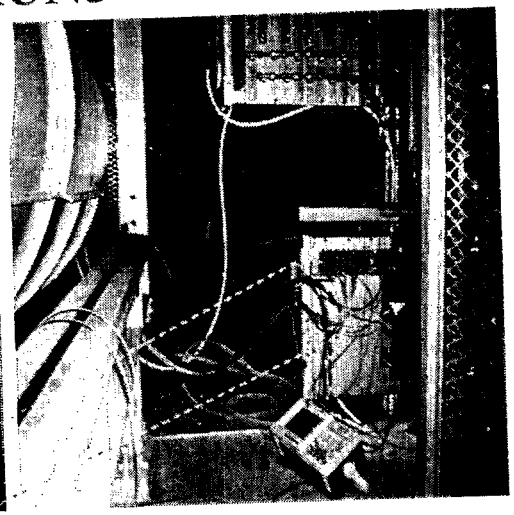
➔ **2-3kHz/cm² in avalanche mode!**

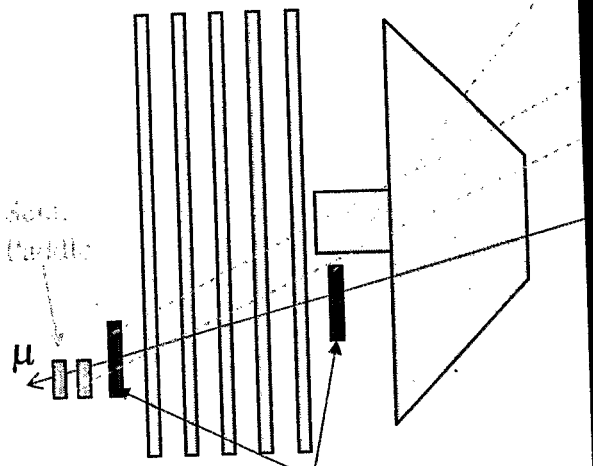
R&D effort: RPC test during RUN5

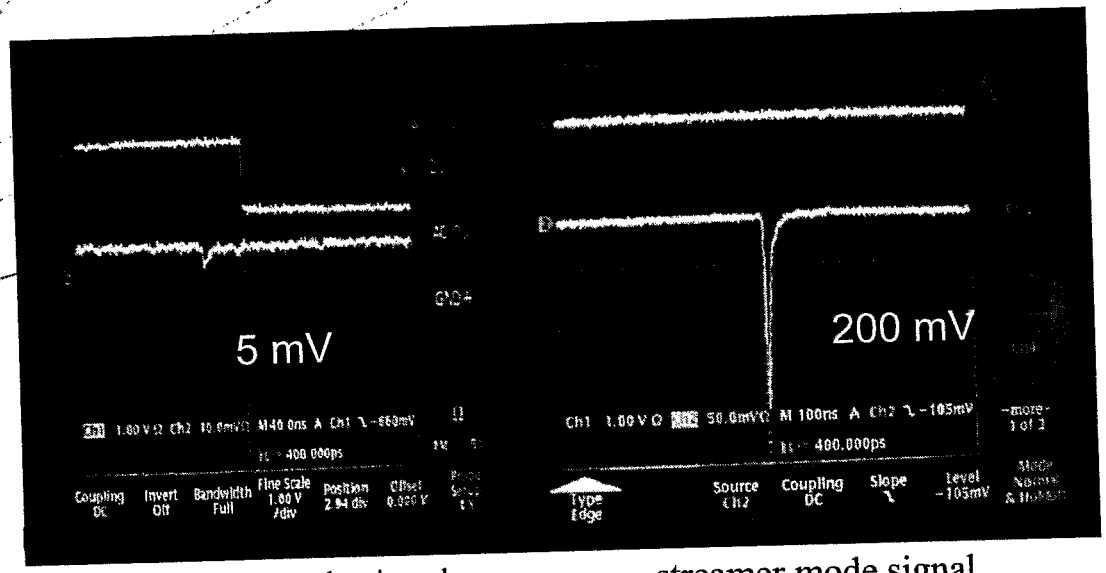
Y. Mao et al., PKU university











avalanche mode signal

streamer mode signal

NSF Proposal Has been Approved !

University of Colorado
Frank Ellinghaus, Ed Kinney, Jamie Nagle, Joseph Seele, Matt Wysocki
University of California at Riverside
Ken Barish, Stefan Bathe, Tim Hester, Xinhua Li, Astrid Morreale, Richard Seto, Alexander Solin
University of Illinois at Urbana Champaign
Mickey Chiu, **Matthias Grosse Perdekamp**, Hiro Hiejima, Alexander Linden-Levy, Cody McCain,
Jen-Chieh Peng, Joshua Rubin, Ralf Seidel
Iowa State University
John Lajoie, John Hill, Gary Sleege
Kyoto University
Kazuya Aoki, Ken-ichi Imai, Naohito Saito, Kohei Shoji
Columbia University
Cheng Yi Chi, William Zajc
RBRC
Gerry Bunce, Wei Xie
Abilene Christian University
Rusty Towell, Larry Isenhower
Peking University
Yajun Mao, Ran Han, Hongxue Ye, Hongtao Liu

Project Schedule

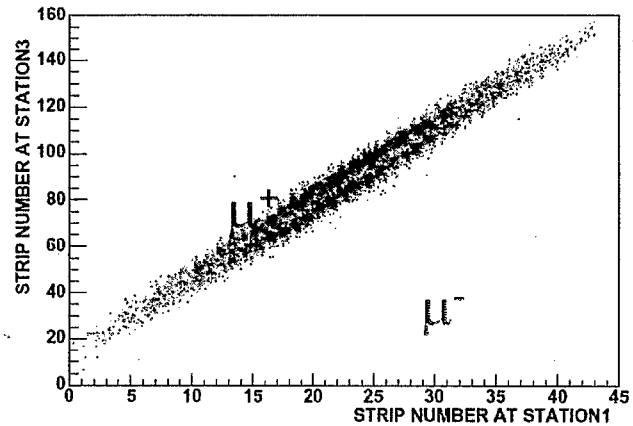
•R&D from 2005-2007

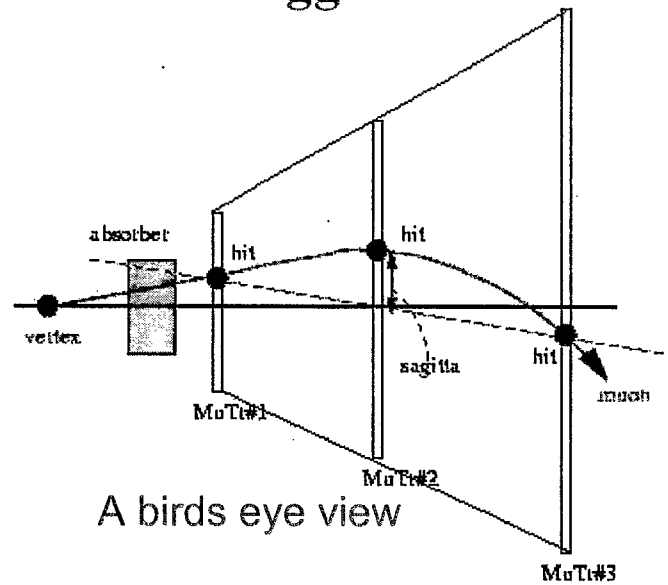
• build RPC for half of the south muon spectrometer by September 2007, install for the run in winter 2007 and 2008.

•build remaining modules for both spectrometers by September 2008

•complete mechanical integration of RPCs into PHENIX by January 2009.

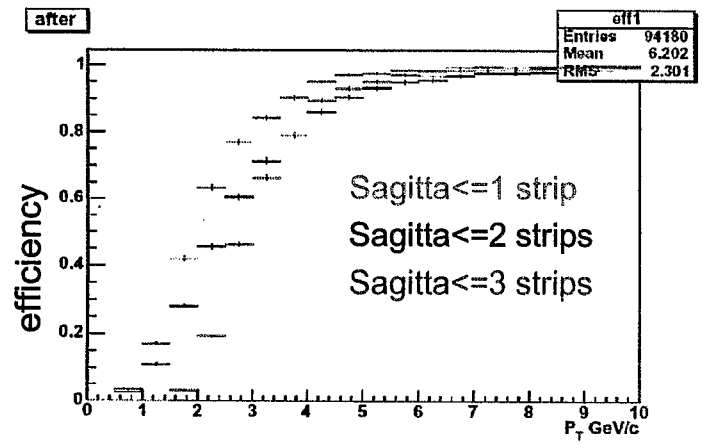
Parallel Project: Muon Tracker Trigger





A birds eye view

	Sagitta<= 1 strip	Sagitta< =2 strips	Sagitta< =3 strips
Rej	23700	10900	7180



Enough rejection power with good efficiency for high pT muons

CURRICULA VITAE

SUMMARY

CURRICULA VITAE - SUMMARY
RBRC FELLOWS/RESEARCH ASSOCIATES/RESEARCHERS

Yasuyuki Akiba **Birthplace:** Tokyo, Japan **DOB:** October 20, 1959
D.S. 1988, University of Tokyo
Experience: Research Associate, Institute for Nuclear Study, University of Tokyo, March 1988 – March 1997;
Research Associate, High Energy Accelerator Research Organization (KEK), April 1997 – March 2003;
Senior Research Scientist, RIKEN, April 2003 – July 2003;
Senior Researcher, RIKEN, August 2003 – present;
RIKEN Spin Program Researcher, RBRC-E, November 2003 – present
Deputy Spokesperson for PHENIX, 2004 - present.

Sinya Aoki **Birthplace:** Tokyo, Japan **DOB:** May 16, 1959
D.S. 1987, University of Tokyo
Experience: Research Associate, Brookhaven National Laboratory, 1987-1989
Post-Doctoral Fellow, SUNY at Stony Brook, 1989-1991
Assistant Professor, U. of Tsukuba, Japan
Lecturer, U. of Tsukuba, 1993-1994
Associate Professor, U. of Tsukuba, 1994-2001
Professor, U. of Tsukuba, April 2001 – present
•Visiting Fellow, joint position with RBRC Theory Group and Tsukuba University, April 1, 2004 – present.
Awards and Honors: Fellowships of the Japan Society for the Promotion of Science for Japanese Junior Scientists, at Physics Department, U. of Tokyo, Japan;
First (FY 2004) JSPS Prize Award, Mathematics; Physical Sciences; Chemistry; Engineering Sciences.

Junkichi Asai **Birthplace:** Kyoto, Japan **DOB:** January 8, 1976
Doctor of Sciences: 2004, University of Tokyo, Japan
Experience: RIKEN Spin Program Research Associate, RBRC-E, April 2004 – June 2005.

Steffen A. Bass **Birthplace:** Frankfurt, Germany **DOB:** May 17, 1968
Ph.D. 1997, J. W. Goethe Universität Frankfurt, Germany
Experience: Feodor Lynen Fellow and Research Associate, Duke University, 1998-99
Visiting Assistant Professor, Michigan State University, 1999
•RHIC Physics Fellow/Assistant Professor--RBRC/Duke, September 1, 2000 – August 31, 2005.
BNL/RBRC Research Collaborator, September 2000 – present.
Awards and Honors: W. E. -Heraeus-Award, W.E.-Heraeus Foundation, Germany, 1993
Feodor-Lynen Fellow, A. v. Humboldt Foundation, Germany, 1997
U.S. Department of Energy Division of Nuclear Physics Outstanding Junior Investigator Award, 2003.

Thomas C. Blum **Birthplace**: USA **DOB**: December 27, 1962
Ph.D. 1995, University of Arizona, Tucson, AZ
Experience: Postdoctoral Fellow, High Energy Theory Group, BNL
RIKEN BNL Fellow, October 1, 1998 – September 30, 2003;
Associate Physicist, Brookhaven National Laboratory, October 2003 – Dec. 2003.
•RHIC Physics Fellow/Assistant Professor—RBRC/U. of Connecticut, Storrs, January 1, 2004 - present.
Awards and Honors: DOE-GANN Fellowship: August 1990 - May 1993;
Year 2005 Department of Energy Outstanding Junior Investigator Award, High Energy Physics.

Christopher Dawson **Birthplace**: Preston, Lancashire, UK **DOB**: July 6, 1973
Ph.D. 1998, University of Southampton, UK
Experience: Research Associate, High Energy Theory Group, BNL
RIKEN BNL Fellow, October 1, 2001 – present

Abhay L. Deshpande **Birthplace**: Mumbai/Bombay, India **DOB**: March 21, 1965
Ph.D. 1994, Yale University
Experience: Visiting Scientist, BNL, 1989-1994 (Member of the BNL-E851 Collaboration)
Visiting Scientist, CERN, 1994-1999 (Member of the SMC Collaboration)
Visiting Scientist, DESY, 1998-Present (Member of the ZEUS Collaboration)
Associate Research Scientist, Yale University, 1994-2000
RIKEN BNL Fellow (Experimental Group), February 2000 – December 31, 2003.
•RHIC Physics Fellow/Assistant Professor-RBRC-E, SUNY, Stony Brook, January 1, 2004 – present.
Awards and Honors: Gibbs Prize in Physics, University of Bombay, 1985.

Takumi Doi **Birthplace**: Hiroshima, Japan **DOB**: November 16, 1976
Ph.D. 2004, Tokyo Institute of Technology, Japan
Experience: Fellowships: The Japan Scholarship Foundation, Department of Physics, Tokyo Institute of Technology, 1999-2001, JSPS Research Fellowships for Young Scientists, Department of Physics, Tokyo Institute of Technology, 2001-2004;
RIKEN Spin Program Research Associate, RBRC, April 1, 2004 – present.
Awards and Honors: Fellowships: JSPS Fellowship, The Iwakuni Foundation for Scholarship, Tokyo University, 1995-1999; Awards: The Tejima Memorial Research Award for Ph.D. Thesis.

Douglas Fields: **Birthplace**: U.S.A. **DOB**: July 2, 1963
Ph.D. 1991, Indiana University, Bloomington
Experience: Postdoctoral Research Associate, Los Alamos National Laboratory, 1992-1995
Research Associate Professor, University of New Mexico, 1995-2001
Member of the PHENIX Collaboration, BNL, 1995-present
•RHIC Physics Fellow/Assistant Professor—RBRC-E, University of New Mexico, September 1, 2001 – present

Yoshinori Fukao **Birthplace**: Aichi, Japan **DOB**: April 5, 1978
B.S. 2001, Kyoto University, Kyoto, Japan
Master Course Student, 2002 – present
Experience: RBRC Young Researcher, Experimental Group, 2002 – 2003.
RIKEN Junior Research Associate, RBRC, Experimental Group,
April 1, 2003 – present.

Kenji Fukushima **Birthplace**: Tokyo, Japan **DOB**: January 29, 1975
Ph.D. . 2002, University of Tokyo, Komaba
Experience: Research Fellow of the Japan Society for the Promotion of Science (JSPS), University of Tokyo, Japan, April 1999 to August 2003; Visiting Scientist, Massachusetts Institute of Technology, Department of Physics, September 2003 - March 2005; RSP Research Associate, RBRC Theory Group, April 2005 - present.
Awards and Honors: JSPS Fellowship

Dominik Gabbert **Birthplace**: Krefeld, Germany **DOB**: June 26, 1979
Vordiplom 2001, Student at Technical University, Munich, Germany for Master Thesis; Visiting Scholar at U. of Illinois, Urbana-Champaign.
Experience: RBRC Young Researcher, RBRC Experimental Group, January 2004 – present.

Yuji Goto **Birthplace**: Shizuoka, Japan **DOB**: November 25, 1965
Ph.D 1996, Kyoto University, Kyoto, Japan
Experience: Research Fellow of the Japan Society for the Promotion of Science, 1994-1996
Postdoctoral Fellow, RIKEN, Japan, 1996-1999
RIKEN BNL Fellow, November 1999 – March 31, 2002
Scientist, RIKEN, April 2002 to March 2003;
Senior Research Scientist, RIKEN, April 2003 – present.
RIKEN Spin Program Researcher, RBRC, April 1, 2002 – present.

Matthias Grosse-Perdekamp
Birthplace: Schwenningen, Germany **DOB**: December 1, 1963
Ph.D. 1995, University of California at Los Angeles
Experience: Associate Research Scientist, Yale University 1995-1998
Research Scientist, Mainz University, 1998-1999
RIKEN BNL Fellow, January 1999 – August 31, 2002.
Member of the PHENIX and BELLE Collaborations;
•RHIC Physics Fellow/Assistant Professor—RBRC-E; University of Illinois, Urbana Champaign, September 1, 2002 – present.
Deputy Spokesperson for PHENIX, 2004 – present.
Awards and Honors: Foreign Scholar Award, UCLA, 1990; Gustav Mie Preis, Freiburg University, 1991.

Koichi Hashimoto **Birthplace**: Fukui, Japan **DOB**: December 20, 1979
M.Sci. 2003, Kanazawa University
Experience: Visiting Student, RBRC, September-October 2003.
RIKEN Spin Program Young Researcher, RBRC Theory Group,
April 2004 – March 2005; RIKEN Jr. Research Associate, April 1, 2005 - present.

Yoshitaka Hatta **Birthplace**: Kyoto, Japan **DOB**: August 5, 1976
Ph.D. 2004, Kyoto University, Department of Physics
Experience: RBRC Young Researcher, Theory Group, RBRC, Spring 2002 – 2003.
RIKEN Junior Research Associate (Theory), 2002 - 2004.
RIKEN Spin Program Research Associate, RBRC Theory, April 1, 2004 – present.

Tetsufumi Hirano **Birthplace**: Kanagawa, Japan **DOB**: September 17, 1972
Ph.D. 2001, Waseda University, Japan
Experience: Research Associate, Waseda University, Japan, April 1999 to March 2001
Postdoctoral Fellow at University of Tokyo, Japan, April 2001 to March 2003.
RIKEN Spin Program Research Associate, RBRC Theory Group,
March 24, 2003 – August 31, 2004.
Visiting Scientist RBRC/Columbia University, September 1, 2004 – present.
Awards and Honors: JPS Theory Award for Distinguished Young Researchers in Nuclear Physics (2002).

Takuma Horaguchi **Birthplace**: Iwate, Japan **DOB**: September 29, 1977
Graduate School: Tokyo University of Science, Japan
Experience: RBRC Young Researcher, Experimental Group, RBRC,
Spring 2002 – 2003.
RIKEN Junior Research Associate (Experiment), April 1, 2003 – present.

Takashi Ichihara **Birthplace**: Japan **DOB**: February 22, 1958
Ph.D. 1987, Kyoto University, Japan
Experience: Research Scientist, RIKEN, Japan, 1987-1995
Senior Research Scientist, RIKEN, Japan, 1995-1998
Assistant Chief Scientist, RIKEN, Japan, 1998
Researcher, RBRC Experimental Group, 1998
RIKEN Spin Program Researcher, November 1999- present

Kei Iida **Birthplace**: Aomori, Japan **DOB**: July 28, 1970
Ph.D. 1998, University of Tokyo
Experience: Postdoctoral Research Fellow, JSPS, U. of Tokyo, April 1998– March 2001;
Visiting Postdoctoral Research Associate, U. of Illinois at Urbana-Champaign, September 1999-March 2001.
RIKEN Special Postdoctoral Researcher, April 2001-March 2004.
RIKEN Fellow, RBRC Theory Group, April 2004-present.
Awards and Honors: Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists, April 1996-March 1998 and April 1998-March 2001.
RIKEN Special Postdoctoral Grant, April 2001-2004.

Takashi Ikeda **Birthplace**: Saitama, Japan **DOB**: December 2, 1973
Ph.D. 2002, University of Tokyo, Japan
Experience: Special Postdoctoral Researcher, RIKEN;
RIKEN Spin Program Research Associate, Theory Group, RBRC,
Spring 2002 – March 2005.

Taku Izubuchi **Birthplace**: Tokyo, Japan **DOB**: February 15, 1970
Ph.D. 1997, University of Tokyo
Experience: Postdoc, Tsukuba University, April 1997-November 1999.
Research Associate (with tenure), Department of Physics, Kanazawa University, December 1999 – February 2001
Brookhaven National Laboratory, High Energy Theory Group, March 2001 – February 2003
Research Associate (with tenure), Department of Physics, Kanazawa University, March 2003 – present.
•RBRC Visiting Fellow with Kanazawa University, April 1, 2003 – present.
Awards and Honors: Japan Society for the Promotion of Science (JSPS), Research Fellowship for Doctor Course, 1994-1997; André Lagarrigue Scholarship at the International School of Subnuclear Physics, Erice, Italy, 1995; JSPS Research Fellowship for Post Doctor, 1997-1999; JSPS Research Fellowship for Research Abroad, 2001-2003.

Sangyong Jeon **Birthplace**: Pusan, Korea **DOB**: March 7, 1964
Ph.D. 1994, University of Washington, Seattle
Postdoctoral Research, University of Washington, Particle Theory Group, February 1995 to June 1995
Postdoctoral Research, University of Minnesota, Nuclear Theory Group, August 1995 to September 1998
Postdoctoral Research, Lawrence Berkeley National Laboratory, Nuclear Science Division, October 1998-December 31, 2000
•RHIC Physics Fellow/Assistant Professor--RBRC/McGill, January 2001 - present
Awards and Honors: Tuition Scholarship, Seoul National University, 1983-1984
Baumgartner Fellowship, University of Washington, 1987-1989
Weis Prize, University of Washington, 1990; Polish Ministry of National Education Award for Outstanding Team Research, 2003.

Osamu Jinnouchi **Birthplace**:Saga, Japan **DOB**: June 13, 1972
Ph.D. 2001, University of Tokyo
Experience: Research Fellow of the Japan Society for the Promotion of Science, January 1999 to March 2001
Contract Researcher of RIKEN, April 2001-2003.
Research Associate, RBRC Experimental Group, April 1, 2003 – Feb. 28, 2005.

Nobuyuki Kamihara **Birthplace**: Yokohama, Japan **DOB**: June 29, 1974
M.Sci. 2002, Master Course of Fundamental Physics, Tokyo Institute of Technology
Experience: Graduate student at Tokyo Institute of Technology/Student Trainee at RIKEN, 2002 - present
RIKEN Spin Program Research Associate, RBRC-Experiment, effective September 2005.

Masashi Kaneta **Birthplace**: Hiroshima, Japan **DOB**: November 5, 1971
Ph.D. 1999, Hiroshima University, Japan
Experience: Member of NA44 Experiment at CERN, 1994-present
Member of Beam-Beam Counter (BBC) Group for PHENIX Experiment, 1994-1999; Member of TOF Detector Group in PHENIX Experiment at RHIC, 1999; Member of STAR Experiment at RHIC, 1999-present;
Postdoctoral Fellow at KEK, 1999; Postdoctoral Fellow Physicist at Lawrence Berkeley National Laboratory, 1999-2002.
Member of STAR Experiment at RHIC, 1999-2003;
Research Associate, BNL, RBRC Experimental Group, Nov. 1, 2002-January 2005.

David M. Kawall **Birthplace**: Glasgow, UK **DOB**: April 13, 1965
Ph.D. 1996, Stanford University
Experience: Associate Research Scientist, Yale University, Physics Department, 1995-2004.
RIKEN BNL Fellow, RBRC Experimental Group, June 1, 2004 – January 2005.
•RHIC Physics Fellow, RBRC Experimental Group/Assistant Professor, University of Massachusettes, Amherst, January 2005 - present
Awards and Honors: G. David Scott Scholarship in Physics, Trinity College Scholarship, Faculty Scholar, Varsity Fund National Admission Scholarship, William R. Hossack Memorial Scholarship in Mathematics and Physics

Stefan A. Kretzer **Birthplace**: Dortmund, Germany **DOB**: November 26, 1968
Ph.D. 1999, University of Dortmund
Experience: Visiting Research Associate at Michigan State University, 2000-2002
Research Associate, Brookhaven National Laboratory, October 2002 –present;
Research Associate, Joint RBRC/Nuclear Theory Group, BNL, April 2003 present.
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Postdoctoral Research Associate at Physics Department, University of California, Riverside, PHENIX at BNL, March 2000 to January 2004;
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Publications

RBRC Experimental Group

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